Author:
O'Connor, Elinor Margaret

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THE EFFECTS OF HEAT STRAIN ON PSYCHOLOGICAL PERFORMANCE

Elinor Margaret O'Connor

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Department of Experimental Psychology

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ABSTRACT

The impact of thermal stress on psychological performance has been the subject of considerable research attention. However, the effects of heat on performance are poorly understood. The literature yields inconsistent results, reflecting methodological shortcomings in previous research, particularly with regard to the definition of the independent variable. Investigators have focused on heat stress *per se* to the neglect of the participants' thermal physiological response. In addition, investigators have typically tested small samples, and have relied on a limited range of performance measures of unknown sensitivity. Few theoretical accounts of performance during thermal stress have been proposed, and these are poorly elaborated.

The principal aim of this research programme was to elucidate the effects of heat on psychological performance. Emphasis was placed on defining the independent variable in terms of physiological strain. Performance was measured using a comprehensive range of sensitive tasks. In the first and second experiments, an innovative water immersion technique was used to control thermal strain precisely. The principal effect of heat strain observed in these experiments was an increase in the speed of performance, without variation in accuracy. This effect was attributed to an increase in nerve conduction velocity associated with raised body temperature. The duration of immersion in the second experiment was fifty percent longer than that in the first, but little variation in performance with the duration of heat strain was evident. In light of the limited external validity of the immersion experiments, subsequent investigation focused on the effects of more realistic sources of thermal strain. A survey of military personnel indicated that occupational exposure to thermal stress is perceived to impair some cognitive and psychomotor functions. The final experiment measured performance during prolonged exposure to heat stress in a climatic chamber. The results indicate that the performance changes observed in the immersion experiments generalize to conditions involving exposure to more realistic sources of heat strain.

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Finally, I wish to thank my colleagues who participated in the experiments. They bore considerable discomfort, and remained co-operative throughout.

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AUTHOR'S DECLARATION

I declare that the work in this dissertation was carried out in accordance with the Regulations of the University of Bristol. The work is original except where indicated by special reference in the text and no part of the dissertation has been submitted for any other degree.

Any views expressed in the dissertation are those of the author and in no way represent those of the University of Bristol.

The dissertation has not been presented to any other University for examination either in the United Kingdom or overseas.

Signed: Date: 25 August 1999

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CHAPTER 1

Introduction

Overview

The psychological impact of exposure to thermal stress has been the subject of considerable research attention. Two principal areas of interest are evident in the literature. The first is concerned with the effects of heat stress on social behaviour and the second addresses the effects of heat on psychological performance. The subject of this dissertation falls into the latter domain.

The impact of thermal stress on psychological performance has been a focus of research interest for five decades, but the effects of heat on performance are poorly understood. The literature yields a largely inconsistent pattern of findings. Much of this inconsistency is attributable to methodological shortcomings in previous research, particularly in the definition and control of the independent variable. The most commonly used method for investigating the effects of heat on performance involves exposing volunteers to elevated environmental temperatures in a climatic chamber. However, previous research has tended to neglect the physiological impact of environmental thermal stress. The thermal physiological response to heat stress varies with the severity and duration of the stress, and with individual differences in acclimatization and body size. Consequently, when the independent variable is defined in terms of the environmental thermal stress, rather than the participants' thermal physiological response, there may be substantial individual and temporal variation in the degree of physiological strain experienced by the participants. Recognition of this source of error provided the impetus for the research programme described in this dissertation.

The general aim of the research was to elucidate the effects of heat on psychological performance. Particular emphasis was placed on defining the independent variable in terms of physiological strain. In the first and second experiments, an innovative warm water immersion technique was used to manipulate thermal strain. This technique permitted the participants' body temperatures to be elevated to and maintained at a specific value with a high degree of precision. The water immersion experiments identified clear and replicable effects of elevation of body temperature on performance. However, because the external validity of the immersion experiments was limited, the later portion of the research programme sought to assess whether the performance changes observed during immersion would generalize to conditions involving exposure to more realistic sources of thermal strain. A survey of military personnel exposed to thermally stressful climates during overseas deployments was conducted to ascertain the perceived performance effects of occupational exposure to heat stress. The final experiment investigated the performance concomitants of heat strain associated with exposure to a thermally stressful environment in a climatic chamber.

The Organization of the Dissertation

This introductory chapter continues with a short account of the physiology of human thermoregulation, with particular emphasis on thermoregulation in the heat. In Chapter 2, the literature on psychological performance in the heat is reviewed; the weaknesses of previous research are highlighted, but, where possible, tentative conclusions are drawn. Chapter 3 discusses a number of methodological issues, including the development of the water immersion technique used to control body temperature in the first and second experiments. These experiments are described in Chapters 4 and 5, respectively. Chapter 6 details the psychological effects of heat stress reported by military personnel during overseas deployments, and Chapter 7 describes the final, climatic chamber experiment. General conclusions are discussed in Chapter 8.

Human Thermoregulation

As homeotherms, humans are able to maintain body temperature at a constant value across a range of environmental thermal conditions. Thermoregulation ensures that the temperature of the core of the body (i.e. the visceral organs, including the brain) is maintained at approximately 37° C. Homeothermy confers several adaptive advantages. Unlike poikilotherms, the activity level of homeotherms is not dependent on the temperature of the environment and vital body tissues are less vulnerable to damage in climatic extremes.

Human heat balance is a function of several variables. The rate of heat storage by the body is determined by metabolic rate and the rate of heat exchange with the environment by conduction, radiation, convection, and evaporation. When the body is in thermal equilibrium the heat produced by metabolism is balanced by the physical transfer of heat to the environment. Variation in the balance between heat production and heat loss is compensated for by physiological regulatory mechanisms that restore thermal equilibrium. For example, a fall in ambient temperature that causes an increase in convective heat loss from the skin will be counteracted by cutaneous vasoconstriction, which lowers skin temperature and reduces convection to the environment. If this reduction in convection is insufficient alone to control heat loss from the body, metabolic heat production will be increased by shivering. In addition to utilizing physiological thermoregulatory mechanisms, humans also demonstrate voluntary behaviours that influence heat exchange with the environment, for example, donning and doffing clothing, and fanning the body.

The seat of thermoregulatory control is the posterior hypothalamus, which integrates signals from the body's temperature receptors and triggers physiological regulatory mechanisms, as necessary. Body temperature is detected by two principal sets of thermoreceptors. The peripheral thermoreceptors, which detect the temperature of the body surface, are located in the skin and are particularly densely distributed in the skin of the face, the palmar surface of the fingers, and the trunk. Two types of cutaneous thermoreceptor have been identified on the basis of differential sensitivity to cold and warmth. The central thermoreceptors, which detect core body temperature, are located in the anterior and pre-optic areas of the hypothalamus, the medulla oblongata, and the spinal cord. Both 'cold' and 'warm' central thermoreceptors have been identified. Temperature sensitive cells have also been identified in the large blood vessels and in the abdomen.

Although core body temperature is regulated, it is not maintained at a constant 'set point', but rather displays a distinct circadian rhythm. The amplitude of the circadian rhythm in core temperature under normal work and sleep patterns is approximately 0.5° C. Core temperature is lowest at about 0500 h. It rises through the day, reaching its acrophase at about 2000 h, and then declines through the night. Mean daily core temperature varies across individuals and, in females, is influenced by the menstrual cycle.

Thermoregulation in the Heat

If metabolic heat production exceeds heat loss from the body, thermoregulatory mechanisms are initiated to restore thermal equilibrium and prevent a rise in core temperature. The primary causes of increased heat storage are exposure to environmental conditions that impede heat transfer and the increased metabolic heat production associated with physical exercise. Heat storage is also increased by impermeable or highly insulative clothing that impedes the dissipation of heat to the environment. When metabolic heat production exceeds heat loss, the first (or at least most rapid) thermoregulatory response is cutaneous vasodilatation. The skin has a rich microcirculation, which is under autonomic control. Reduction of sympathetic activity causes these vessels to dilate and the resultant rise in skin temperature increases convective heat loss to the environment. Vasodilatation is elicited by warming of the skin on exposure to a hot environment. Vasodilatation also occurs in response to a rise in core temperature. As cutaneous vasodilatation necessitates a compensatory rise in cardiac output to maintain arterial blood pressure, significant vasodilatation is accompanied by elevation of heart rate.

If vasodilatation is insufficient alone to restore thermal equilibrium, sweating occurs. Sweat is an ultrafiltrate of plasma secreted by the eccrine glands of the skin; the evaporation of sweat is a very effective heat loss mechanism. The skin contains approximately three million eccrine glands. These are distributed over the entire skin surface, but are concentrated on the forehead, the thighs, the palms, and the soles. Small quantities of sweat are secreted continuously by the skin (about 500 ml of sweat are secreted each day in insensible perspiration), but an increase in skin or core temperature triggers more profuse sweating via cholinergic sympathetic pathways. The rate of sweating is altered by varying the number of eccrine glands recruited, the rate of secretion by the glands or both in combination. Maximal sweat rate can be as high as two litres per hour, but this rate can be maintained only for short periods; a more typical rate during exposure to heat stress is one litre per hour.

Exposure to high environmental temperatures over a period of several days or repeated strenuous exercise produces acclimatization. Thermoregulation becomes more effective due primarily to a reduction in the threshold core temperature at which sweating occurs and an increase in the secretory capacity of the eccrine glands.

Hyperthermia

The heat loss mechanisms described above are generally effective in maintaining the thermal equilibrium of the body and preventing a rise in core temperature. However, these mechanisms have a finite capacity and under some circumstances they can be insufficient to prevent elevation of core temperature. Hyperthermia can occur if the environmental thermal conditions significantly compromise the efficacy of the body's heat loss mechanisms. High environmental dry bulb temperatures impede convective heat loss even when cutaneous vasodilatation is maximal. If the air temperature exceeds skin temperature, not only is convective heat loss prevented, but the body may gain heat from the environment. High environmental humidity impedes the evaporation of sweat. Hyperthermia can also occur if the metabolic demands of strenuous physical exercise exceed the capacity of the body's heat loss mechanisms. The risk of hyperthermia is increased when exposure to environmental heat stress, high physical workload, and the wearing of impermeable or highly insulative clothing (e.g. protective work clothing) occur in combination.

Elevation of core temperature by about one degree Celsius produces significant discomfort and fatigue. These symptoms tend to intensify as core temperature rises further. Significant vasodilatation can cause syncope. Dehydration can occur if fluid intake is inadequate to compensate for a high sweat rate. At a core temperature of approximately 40° C, the eccrine glands cease to function. This phenomenon is termed heat stroke, and represents a life-threatening emergency. The loss of evaporative cooling allows body temperature to rise still further, producing drowsiness, impairment of co-ordination, hallucinations, and, eventually, loss of consciousness and convulsions. Elevation of core temperature to 42° C can be fatal, typically as a result of cardiac failure.

CHAPTER 2

Review of the Literature

Introduction

The effects of thermal stress on psychological performance have been a focus of research interest since Mackworth's seminal studies in the 1940s of the impact of heat on the cognitive and psychomotor performance of military personnel. However, despite considerable research attention, the effects of heat stress on performance remain unclear. Review of the literature reveals an inconsistent pattern of results, which is due, in large part, to methodological shortcomings that blight much of the research. Few theoretical accounts of the relationship between heat and performance have been proposed, and these are poorly developed.

Methodological Weaknesses in Previous Research

The Definition of the Independent Variable

The most significant factor underlying the inconsistent pattern of findings in the literature lies in the definition and control of the independent variable. The most commonly used technique for manipulating heat stress involves exposing volunteers to elevated environmental temperatures in a climatic chamber. However, there has been little consistency across experiments either in the environmental conditions selected for control and experimental exposures or in the duration of exposures. This lack of consistency greatly hampers the comparison of results.

A more significant problem is that investigators have tended to focus on the environmental stress *per se*, rather than on the thermal physiological response to the environment. Of the studies included in this review in which the participants were exposed to raised environmental temperatures, more than fifty percent did not report any thermal physiological data. Just twelve percent provided a comprehensive account of the participants' thermal physiological response, including details of core and skin temperatures, sweat loss, and heart rate. This lack of attention to the participants' physiological state is also reflected in a failure to consider variables that affect thermoregulatory responses to heat stress. For example, several environmental variables have an impact on human heat exchange. These include dry bulb temperature, relative humidity, radiant heat load, and air velocity. However, these have not always been reported in full by investigators. Similarly, in forty percent of the experiments reviewed, the participants' clothing was not standardized.

This focus on environmental stress rather than physiological strain introduces a significant source of error. The core body temperature response to environmental heat stress varies with the intensity of the stress, the duration of the exposure, and with variables such as physical work rate and the type of clothing worn. In addition, individual differences in body size and shape, and in physiological characteristics such as acclimatization affect the core temperature response to heat stress. Consequently, when the independent variable is defined in terms of the environmental stress there may be substantial individual and temporal variation in the degree of thermal physiological strain experienced by experimental participants.

Sample Size

Experimental investigations of the effects of heat stress on performance have typically utilized small samples. Sixty percent of the experiments included in this review used samples of twelve individuals or fewer. Twenty percent utilized samples of eight individuals or fewer. These observations suggest that the statistical power of much of the published research may be limited.

The Range and Sensitivity of Performance Measures

Previous research has measured the effects of heat stress on a limited range of cognitive and psychomotor functions. Investigators have concentrated on the impact of heat on reaction time, vigilance, and tracking, and to a lesser extent, on reasoning (primarily mathematical reasoning). There is a dearth of data on the effects of heat stress on attention, memory, and verbal and spatial reasoning.

In much of the thermal stress literature, it appears that performance measures have been selected on a largely arbitrary basis. There is little evidence that researchers have assessed the sensitivity of the tasks used to measure the impact of heat stress on psychological performance.

The Organization of the Literature Review

This review is divided into two principal sections. The first considers the effects of exposure to heat stress on specific cognitive and psychomotor functions. In the second section, theoretical accounts of the relationship between heat stress and performance are reviewed.

The Effects of Heat Stress on Psychological Performance

Classifying Psychological Performance

It is self-evident that a review of research on psychological performance during thermal stress should consider the effects of heat according to task type. However, some reviewers have categorized performance using classification schemes that appear too general to be useful. For example, Ramsey (1995) classified several conceptually diverse performance tasks into just two categories: 'mental' tasks, which included measures of reaction time and arithmetic, and 'perceptual motor' tasks, which incorporated tracking and vigilance tasks. Hancock (1982) classified performance into just three categories (mental and cognitive skills, tracking, and dual-task performance). More complex classification schemes were used in reviews by Grether (1973) and Hygge (1992).

The present review considers the effects of heat on four categories of tasks: reaction time, vigilance, tracking, and reasoning. As noted above, the literature focuses almost exclusively on these functions. A small number of miscellaneous tasks are considered separately.

Quantifying Thermal Stress

A complete description of the thermal environment requires reference to several variables, including dry bulb temperature, humidity, radiant heat load, and air velocity. To aid the comparison of experiments in which a number of environmental variables were reported several reviews of the effects of heat on performance have converted the environmental data into a single index of thermal stress. However, this approach is of limited value because no single heat stress index is entirely appropriate for the purpose.

In reviews by Grether (1973) and Hygge (1992), the environmental data were converted to the Effective Temperature (ET) scale, which combines dry bulb temperature, humidity, and air velocity into a single figure. Similarly, Hancock (1982) employed the ET index to define tolerance limits for psychological performance in hot environments (revised by Hancock and Vasmatzidis, 1998). However, ET is a poor predictor of the physiological response to a thermally stressful environment. In particular, it tends to underestimate the impact of high humidity and low air velocity at high dry bulb temperatures, and to overestimate the effect of high humidity at lower air temperatures (Allan, 1988). More significantly, there is evidence that different combinations of dry bulb temperature, humidity, and air velocity with equal ET values affect psychological performance differently (e.g. Pepler, 1958; Sharma, Pichan, and Panwar, 1983).

In a review by Ramsey (1995), the environmental data were converted into values on the Wet Bulb Globe Temperature (WBGT) index. This index combines dry bulb temperature, black globe temperature, and humidity level into a single value. The WBGT index was developed to predict military heat casualty rates during desert operations, and as a predictor of physiological strain, it is most accurate under the conditions for which it was devised, that is, environments with a significant radiant heat load (Allan, 1988). However, radiant heat has rarely been manipulated in psychological performance research. Indeed, Ramsey was required to estimate black globe temperature values for the majority of the papers included in his review.

The environmental variables reported in this review are dry bulb temperature (T_{db}), relative humidity (rh), and air velocity. In several papers, these data were not reported in full. Temperature values originally reported in Fahrenheit have been converted to the Celsius scale (rounded to the nearest whole degree), and imperial measures have been converted to metric indices.

The Effects of Heat Stress on Reaction Time

Simple Reaction Time

In a review of the effects of thermal stress on psychological performance, Grether (1973) concluded that heat stress shortens simple reaction time. However, this conclusion was based on just three studies, one of which (Benor and Shvartz, 1971) reported negative findings. More extensive examination of the literature does not support Grether's conclusion.

One of the experiments cited by Grether was conducted by Lovingood, Blyth, Peacock, and Lindsey (1967), who exposed volunteers for three and a half hours to 23° and 52 ° C T_{db}. The humidity levels in both conditions were highly variable. Rectal temperature, heart rate, and sweat loss were significantly elevated in the hot condition. Simple reaction time to the illumination of a light was measured at hourly intervals throughout the exposures. Reaction time was shorter in the heat.

Ramsey and Pai (1975) reported that simple reaction time to a visual stimulus (which was not described) measured in a sample of females did not vary across exposures to 29°, 40°, 46°, and 52° C T_{db}, with 40% rh. The duration of the exposures ranged from two hours at the lowest temperature to thirty minutes at the highest temperature. The authors contrasted these results with those of a study using the same procedures, but conducted with males, which reported shorter simple reaction times in the hottest condition (Ramsey, 1975, cited in Ramsey and Pai, 1975). The origin of this difference in the results is unclear. Details of the experiments are scant; most significantly, physiological data were not reported so any sex differences in thermal physiological response were concealed.

In a well-controlled experiment conducted by Razmjou and Kjellberg (1992), volunteers were exposed for one hour and ten minutes to 40° C T_{db} with 30% rh. In the control condition, the dry bulb temperature was 22° C with 40% rh. To increase metabolic heat production the participants exercised during the first ten minutes of the exposures. In the final sixty minutes of the exposures, simple reaction time to the illumination of a light and four-choice serial reaction time were measured. In the hot condition, mean rectal temperature during performance measurement was slightly but significantly increased (37.4° C compared with 37.2° in the control condition) and heart rate was elevated. Thermal stress lengthened simple reaction time.

A subsequent study by Razmjou (1996) measured performance on a primary, four-choice, serial reaction task and a secondary measure of simple reaction time to the presentation of a tone during exposure to 22° and 40° C T_{db}, with 50% rh. The participants did not exercise, but mean core temperatures were comparable with those reported in the previous experiment. No significant variation in simple reaction time was observed, but trends in the data are consistent with the results of the previous study. The absence of a significant effect may reflect differences between the simple reaction tasks used in the two experiments. In the first study, visual stimuli were used; in the second, the task was presented as a secondary measure, and auditory stimuli were utilized. Alternatively, the absence of significant variation in simple reaction time may stem from the use of a smaller sample in the second experiment (twelve participants, compared with twenty in the first study).

Benor and Shvartz (1971) measured simple reaction time to a light flash as volunteers exercised while wearing an impermeable suit in dry bulb temperatures ranging from 30° to 50° C. The volunteers were exposed to each temperature condition twice, once while wearing a liquid cooled garment under the impermeable suit to maintain body temperatures at normal values. The duration of the exposures varied according to the participants' physiological tolerance, but did not exceed two hours. In the absence of cooling, mean rectal and skin temperatures, heart rate, and sweat loss were elevated; physiological strain intensified as the air temperature increased. Reaction time was unaffected by heat strain. The lack of significant change in performance may be due to the small sample (seven people were tested), but given the intensity of the thermal strain experienced by the participants, the absence even of discernible trends is not readily explicable.

In summary, research on the effects of thermal stress on simple reaction time has yielded inconsistent findings. The results reported by Lovingood et al (1967) and Ramsey (Ramsey, 1975, cited in Ramsey and Pai, 1975) suggest that exposure to very high dry bulb temperatures lowers reaction time. The well-controlled studies conducted by Razmjou and his colleague (Razmjou and Kjellberg, 1992; Razmjou, 1996) indicate that thermal stress increases simple reaction time. However, Benor and Shvartz (1971) reported negative findings, even in extreme conditions.

Choice Reaction Time

Few published data on the effects of heat on choice reaction time are available. Four studies were identified, but a number of these are compromised by methodological weaknesses.

Bell, Loomis, and Cervone (1982) exposed volunteers to 22° C T_{db} with 46% rh, and 37° C T_{db} with 43% rh. The duration of the exposures was not specified, but appears to have been approximately twenty minutes. Thermal physiological data were not reported. Four-choice reaction time to the illumination of lights tended to be longer in the hot condition. Accuracy data were not recorded.

Grether, Harris, Mohr, Nixon, Ohlbaum, Sommer, Thaler, and Veghte (1971) administered a two-choice reaction task (the stimuli were illumination of a red light and extinction of a green light) in conjunction with compensatory tracking and auditory reception tasks during the final thirty minutes of a one-and-a-half-hour exposure to 22° and 50° C T_{db}, with an air velocity of 0.4 m/s. Relative humidity was not controlled. Three further conditions were included in the experiment: under the control environmental temperature, the participants were exposed during performance testing to (i) 105 dB continuous noise and to (ii) 5 Hz sinusoidal vibration, and (iii) under the experimental environmental temperature, the participants were exposed to noise and vibration in combination. Rectal and skin temperatures, heart rate, and sweat loss were significantly elevated in the heat. Reaction time to the red light did not vary significantly across the conditions. Reaction time to the extinction of the green light was longer in the stressful conditions than in the control condition, but did not differ significantly across the stressful conditions. Accuracy data were not reported. The absence of differential effects of the experimental conditions on reaction time suggests that the task may have been relatively insensitive to the impact of environmental stressors. In addition, a rather small sample (ten individuals) was tested.

Hancock and Dirkin (1982) used a heated helmet to raise the temperature of the external auditory canal by 5° C above baseline for a period of thirty minutes, during which a visual, four-choice reaction task was administered. Reaction time increased and accuracy was enhanced during heating. In the 'placebo' condition, in which a non-heated helmet was worn, a mean rise in auditory canal temperature of 1° C was observed, and this was associated with an increase in reaction time (and a non-significant reduction in error) compared with performance when the helmet was not worn. The researchers attributed these performance changes to an increase in cortical temperature. However, this conclusion is questionable. Auditory canal temperature is valid as an index of core body temperature only if the canal is insulated to prevent contamination by the temperature of the external environment. It is not clear that this precaution was taken in this experiment; indeed, the very rapid rise in auditory canal temperature when heating was started (approximately 4° C in ten minutes) indicates contamination of the measure by the local environmental temperature. No other physiological data were reported although the authors noted that, in a previous study, the helmet technique did not affect heart rate. It is unlikely that the participants in this experiment experienced significant heat strain. It appears that the performance changes observed were associated with variation in the temperature of the immediate environment of the head.

Provins and Bell (1970) administered a central, visual, five-choice reaction task in conjunction with a secondary, visual detection task during the second and third hours of three-hour exposures to 20° C T_{db} with 60% rh, and 40° C T_{db} with 70% rh, with an air velocity of 0.3 m/s. Oral temperature was significantly elevated in the heat. Two rates of stimulus presentation were utilized in the choice reaction task. Reaction time data were not recorded. During the first hour of performance testing, accuracy on the faster paced task was higher in the hot than in the control condition. The error rate on the slower paced task was too low to be analysed.

In conclusion, the results of these studies indicate that choice reaction time increases during exposure to heat stress. The findings obtained by Hancock and Dirkin (1982), and Provins and Bell (1970) suggest that heat enhances choice reaction accuracy. However, as a result of methodological shortcomings in a number of these experiments, these conclusions must be considered tentative.

Serial Reaction Time

Several researchers have investigated the effects of heat stress on serial reaction time to visual stimuli. The methodological quality of these studies is rather variable, but a largely consistent pattern of results emerges.

Pepler (1959) measured performance on a five-choice serial reaction task during the latter half of a one-hour exposure to 21°C T_{db} with 75% rh, and 38° C T_{db} with 65% rh, with an air velocity of 0.5 m/s. Physiological data were not reported. The number of errors increased in the heat, but the number of correct responses was unaffected, indicating an increase in overall response speed. The number of gaps in responding was greater during thermal stress.

These findings were replicated by Poulton and his colleagues (Poulton, Edwards, and Colquhoun, 1974; Poulton and Edwards, 1974b), who administered a five-choice serial reaction task during the second thirty minute period of a one-and-a-half-hour exposure to environmental conditions similar to those used by Pepler. In a similar experiment, Poulton and Edwards (1974a) reported a non-significant increase in error rate on a five-choice task in the heat. The correct response rate and the number of response gaps were unaffected by thermal stress (mean values were not reported so trends cannot be discerned). However, the results of these studies must be interpreted with caution. The experiments investigated the individual and combined effects of heat and other stressors using repeated-measures designs. In each experiment, the order in which the participants were exposed to the conditions was determined using a latin square, but the design was not balanced for first-order carry-over effects.

Hygge (1991) measured five-choice serial reaction time in the final twenty minutes of a two-and-a-half-hour exposure to 19° and 27° C T_{db}, with 80-90% rh. Thermal physiological data were not reported. In the hot condition, reaction time was shorter and the number of gaps in responding was reduced. Accuracy was apparently unaffected by heat (mean error rates were not reported).

Razmjou and Kjellberg (1992) administered a four-choice serial reaction task in the final sixty minutes of a one hour and ten minute exposure to 22° C T_{db} with 40% rh, and 40° C T_{db} with 30% rh. A non-significant reduction in reaction time and a significant increase in error rate were observed in the hot condition. The number of gaps in responding was too low to be analysed. In a similar study (Razmjou, 1996), volunteers completed a central, four-choice serial reaction task (which used slightly different visual stimuli to those in the previous experiment) in conjunction with a secondary, simple reaction task. As in the previous experiment, a non-significant reduction in choice reaction time was observed in the heat. Accuracy was unaffected by thermal stress. The number of gaps in responding was not reported.

In summary, the results of the studies discussed above suggest that serial reaction time is enhanced by heat stress, typically at the cost of accuracy. Some investigators have reported negative findings, but scrutiny of the data reveals trends that support the conclusion that exposure to heat stress shortens serial reaction time. Of those studies that have reported gaps in responding, the majority indicate that heat increases the number of response gaps.

Reaction Time during Heat Stress: The Impact of Feedback and Mental Effort

Razmjou and Kjellberg (1992) reported an increase in simple reaction time and a non-significant reduction in serial reaction time during thermal stress. Serial reaction accuracy deteriorated in the heat. Those participants who exerted greater mental effort (indicated by lower heart rate variability) demonstrated shorter reaction times in the serial reaction task during heat stress. However, because this experiment utilized a repeated-measures design, the validity of reporting the results of a sub-group of the sample is questionable, as relevant independent variables may not have been appropriately balanced across these participants.

Razmjou (1996) investigated the impact of workload and feedback on the effects of heat on a primary, serial reaction task and a secondary, simple reaction task. No significant variation in performance with thermal stress was observed. There was no evidence that either workload or feedback affected performance in the heat.

Speed of Performance during Heat Stress: Additional Data

Additional data on the effects of thermal stress on reaction time have been gleaned from studies of the impact of heat on more complex mental functions. However, the findings are largely inconsistent and they shed little light on the effect of heat stress on general performance speed.

Research on vigilance in the heat has reported contradictory findings regarding the speed of reaction to signals. Several studies have obtained negative results (e.g. Colquhoun and Goldman, 1972; Poulton and Edwards, 1974a, b; Poulton et al, 1974). Wilkinson, Fox, Goldsmith, Hampton, and Lewis (1964) found that elevation of oral temperature enhanced the speed of response to signals in an auditory vigilance task. Wyon, Wyon, and Norin (1996) reported that reaction time to signals increased during exposure to heat stress.

Wilkinson et al (1964) reported that thermal strain impaired the speed (and the accuracy) of mathematical reasoning. However, Holland, Sayers, Keatinge, Davis, and Peswani (1985) found that elevation of core and skin temperatures enhanced the speed of both arithmetic and verbal reasoning (accuracy was unaffected).

The Effects of Heat Stress on Vigilance

The effects of heat stress on visual and auditory vigilance have been the focus of considerable research attention. It is unfortunate that a substantial proportion of this research has concentrated on the effects of heat on signal detection rate alone. There is a dearth of data on the impact of heat on false detections, which hinders identification of the origin of changes in signal detection rate during exposure to thermal stress.

Mackworth (1950) administered the Clock Test visual vigilance task to acclimatized volunteers during a two-hour exposure to 24° C T_{db} with 55% rh, 29° C T_{db} with 65% rh, 35° C T_{db} with 65% rh, and 41° C T_{db} with 55% rh. In each condition, the air velocity was 0.5 m/s. Signal detection rate was higher and the median reaction time to signals was lower during exposure to 29° C T_{db} than in the cooler or hotter conditions. Signal detection rate was poorer in the second than the first hour of exposure to 35° and 41° C T_{db}. False detection rates were not reported. Pepler (1958) repeated the experiment, but selected different exposure conditions to those used by Mackworth: 24° C T_{db} with 55% rh, 32° C T_{db} with 65% rh, and 49° C T_{db} with 20% rh. The air velocity in each condition was 0.4 m/s. Signal detection rate was higher at 32° C T_{db} than at lower or higher environmental temperatures. Performance was poorer in the second than the first hour of exposure to 24° and 49° C T_{db}. False detection rates and reaction times were not reported.

The results of these two experiments suggest that moderate heat stress enhances signal detection. However, given that the participants wore only shorts, it is conceivable that the environmental temperature in the coolest condition (i.e. 24° C T_{db} in both experiments) was too low for comfort. Indeed, Mackworth reported a mean decrease in rectal temperature of 0.5° C during exposure to 24° C T_{db} (Pepler did not report change in core temperature during exposures). Thus, the enhancement of signal detection rates at moderately raised environmental temperatures may reflect a deterioration in performance due to discomfort in the cooler conditions. Elevation of the dry bulb temperature to 35° C or more resulted in a deterioration in signal detection.

Mortagy and Ramsey (1973), and Wyon et al (1996) reported reductions in signal detection rates during exposure to elevated environmental temperatures. Mortagy and Ramsey's results indicate that the deterioration in signal detection in the heat was exacerbated by longer work periods and higher work/rest ratios. Neither study reported false detection rates.

Bell, Provins, and Hiorns (1964) reported that visual signal detection rates were unaffected by heat stress, even when the environmental temperatures were extreme (i.e. > 50° T_{db}). However, these results must be interpreted with caution, as the participants were exposed to continuous noise with an intensity of 85-95 dB in all of the conditions. Iampietro, Chiles, Higgins, and Gibbons (1969) reported negative findings at 60° and 71° C T_{db}, which may have been due to the relatively short duration of the exposures in their experiment (i.e. thirty minutes). False detection rates were not reported in either study.

A series of experiments conducted by Poulton and his colleagues investigated the effects of thermal stress on both signal detection and false detection rates. Poulton et al (1974) reported that heat stress reduced signal detection rate in the Wilkinson auditory vigilance task, which was completed during the final thirty minutes of a one-and-a-half-hour exposure to 20° C T_{db} with 75% rh, and 38° C T_{db} with 65% rh. The false detection rate was unaffected by thermal stress. These findings were replicated by Poulton and Edwards (1974b). These results suggest that the deterioration in signal detection in the heat was due to a decrease in signal detectability. However, in a further study, thermal stress increased the false detection rate in a visual analogue of the Wilkinson task (Poulton and Edwards, 1974a). This result suggests that the decision criterion was reduced, but the reduction in signal detection rate in the heat (albeit non-significant) is inconsistent with this conclusion. This pattern of results is difficult to interpret. The false detection rate was low (1 - 2%), so a small change in criterion could, conceivably, have produced a significant effect in the false alarm rate without a concomitant significant change in the detection rate. The direction of the trend in detection rate was, however, inconsistent with a reduction in the decision criterion. In all three experiments, reaction time to signals was unaffected by thermal stress. As discussed previously, the results of these studies must be interpreted with caution, as the experiments were not balanced for first-order carry-over effects.

Benor and Shvartz (1971) provided additional evidence that signal detectability was reduced during heat stress. Furthermore, their results suggest that the change in detectability was related to thermal strain rather than to the environmental temperature (Poulton and his colleagues did not report physiological data). Auditory vigilance was measured as volunteers exercised while wearing an impermeable suit in dry bulb temperatures ranging from 30° to 50° C. The participants completed each condition twice, once while wearing a liquid cooled garment under the impermeable suit to maintain body temperatures at normal values. Without cooling, mean rectal and skin temperatures, heart rate and sweat loss were substantially elevated; thermal strain was more marked as the air temperature increased. In the absence of cooling, signal detection rate was poorer, deteriorating progressively as environmental temperature and physiological strain increased. Signal detection rate was lower in the second than the first half of exposures; this duration-related impairment was more marked at higher air temperatures. When the participants were cooled, signal detection rate was unaffected by ambient temperature. The false detection rate was low. Fewer false detections were observed when the participants were cooled. With or without cooling, the false detection rate did not vary significantly with the environmental temperature. Reaction times to signals were not reported.

On balance, the results of the experiments described above indicate that heat stress reduces signal detection rate, and provide some evidence that this effect reflects a decrease in signal detectability rather than a change in the decision criterion. However, two studies have reported an enhancement of signal detection associated with thermal strain. The results of one of these suggest that the increase in signal detection rate had its origin in a reduction in the decision criterion.

In a well-controlled experiment, Wilkinson et al (1964) used a specialized clothing assembly to maintain oral temperature at specific, elevated values. Auditory vigilance was measured over a period of two hours while oral temperature was maintained at 37.3°, 37.9°, and 38.5° C, and while temperature was maintained at its baseline value. Compared with performance in the control condition, signal detection rate was higher and reaction times to signals were reduced when oral temperature was raised to 38.5° C. The signal detection rate varied with the duration of thermal strain; the detection rate increased over the course of the period during which oral temperature was maintained at 38.5° C. False detection data were not reported.

Colquhoun and Goldman (1972) administered a visual analogue of the Wilkinson vigilance task during the second hour of a two-hour exposure to 24° C T_{db} with 40% rh, and 39° C T_{db} with 70% rh, with an air velocity of 1.3 m/s. In the first hour, the participants either rested or they exercised for periods ranging from ten to thirty minutes. When the participants responded to signals, they were required to indicate their degree of confidence that a signal had been presented. In the hot condition, mean rectal temperature during performance testing increased with the duration of exercise, ranging from 38° C when the volunteers had rested to 38.6° C following thirty minutes exercise. There were no significant effects of environmental temperature on signal detection rate, false detection rate or reaction time to signals. However, analysis of the responses in which the participants had indicated a high degree of confidence indicated that, in the hot condition, signal detection rate was higher on completion of thirty minutes exercise than following rest. The false detection rate increased with the duration of exercise in the heat. The authors reported that further analysis revealed a lowering of the decision criterion (as indicated by the value of β) in the hot condition as the duration of exercise (and the intensity of physiological strain) increased.

In conclusion, research on the impact of thermal stress on vigilance indicates that heat stress reduces signal detection rate. There is some evidence to suggest, firstly, that the deterioration in signal detection stems from a reduction in signal detectability, and secondly, that this change in detectability is related to the intensity of the physiological strain experienced during thermal stress. However, two experiments have obtained results that contradict this general pattern of findings (Wilkinson et al, 1964; Colquhoun and Goldman, 1972). Both studies reported that thermal strain increased signal detection rate, and Colquhoun and Goldman presented evidence that the improvement in signal detection stemmed from a reduction in the decision criterion. The inconsistency between these two sets of findings is not readily resolved.

The Effects of Heat Stress on Tracking

Research on the impact of thermal stress on tracking is largely consistent in indicating that performance is impaired in the heat. Review of the literature reveals evidence that the effects of heat on tracking are influenced by task duration and demand. This highlights the importance of precise definition of task variables in performance research; such details are typically absent from the heat stress literature.

Mackworth (1950) exposed volunteers for three hours to 29°, 32°, 35°, 38°, and 41° C T_{db}, with 65% rh and an air velocity of 0.5 m/s. In the second half of each hour of the exposures, the participants completed a one-dimension, pursuit tracking task in which the control lever was weighted by 50 lb (23 kg). Error rose as the environmental temperature increased (mean values were not tested for statistical significance). However, because the control lever was heavily weighted, the results may reflect a reduction in the capacity for strenuous physical work in the heat rather than a deterioration in psychomotor performance. Pepler (1958) repeated this experiment, but reduced the weighting of the control lever to 16 lb (7 kg), which was reported to be the optimal weighting for performance of the task. Pepler also omitted the hottest condition used by Mackworth. Sweat loss increased as the environmental temperature rose; body temperatures were not reported. Tracking error was lower at 32° T_{db} than at 29°, 35°, and 38° T_{db}.

Azer, McNall, and Leung (1972) measured performance on a primary, one-dimension, compensatory tracking task and a secondary, lights detection task during a two-hour exposure to 35° C T_{db} with either 50% or 75% rh, and 38° C T_{db} with 50% rh. The air velocity was 0.2 m/s. Independent groups of seven volunteers were exposed to the control condition (24° C T_{db} with 50% rh) and one of the three hot conditions. Body temperatures, heart rate, and sweat loss increased during thermal stress; elevation of core temperature was most marked at 35° C T_{db} with 75% rh. Compared with the control condition, tracking accuracy was poorer in each of the experimental conditions, but this difference was significant only in the hottest condition. Performance did not vary with the duration of exposure to thermal stress. Tracking performance was not compared across the three stressful conditions. Bell (1978) administered a primary, pursuit rotor task with a secondary, auditory monitoring task in the latter half of a thirty-minute exposure to 22°, 29°, and 35° C T_{db}, with 40-50% rh. Thermal physiological data were not reported. Time on target tended to deteriorate as environmental temperature increased.

In an experiment by Poulton et al (1974), volunteers completed a primary, one-dimension, pursuit tracking task in conjunction with a secondary, lights detection task during the first thirty minutes of a one-and-a-half-hour exposure to 20° C T_{db} with 75% rh, and 38° C T_{db} with 65% rh. Tracking error was higher in the heat. Poulton and Edwards (1974a) conducted a similar experiment, but raised the relative humidity in the experimental condition to 70% and increased the frequency of the target movement from 25 to 45 cycles per minute. Tracking error in the first half of the task was higher during thermal stress. However, a subsequent study using the same environmental conditions and performance measures found that tracking error in the first half of the task was *lower* in the heat (Poulton and Edwards, 1974b). The authors proposed that the inconsistent results of these two studies were attributable to the impact of other conditions in the experiments. The first study examined the individual and combined effects of heat stress and noise on performance. Interpreting the results from the perspective of classic arousal theory, the authors argued that, relative to noise, thermal stress lowered arousal, hence performance was poorer in the heat compared with the control condition. The second experiment investigated the effects of thermal stress and l-hyoscine hydrobromide; heat stress increased arousal relative to hyoscine and, consequently, performance was better in the heat than in the control condition. However, as noted previously, these studies were compromised by the use of a repeated-measures experimental design that was not balanced for first-order carry-over effects.

Tracking during Heat Stress: The Impact of Task Variables

Bursill (1958) described three experiments in which a primary, one-dimension, pursuit tracking task was administered in combination with a lights detection task during exposure to 21° and 41° C T_{db}, with 60% rh and an air velocity of 0.6 m/s. Thermal physiological data were not reported. The duration of the exposures was one hour and forty-five minutes in the first experiment and two hours and forty-five minutes in the second. Performance was measured during the final forty-five minutes of the exposures. Time on target was poorer during thermal stress. Performance deteriorated more with time on task in the longer than in the shorter heat exposure. The third experiment repeated the conditions of the first, but the task demand was reduced by decreasing the frequency of movement of the target. Performance was unaffected by thermal stress (mean values were not reported so trends cannot be discerned). However, this negative finding must be interpreted cautiously, as the sample tested was substantially smaller than that used in the first experiment (six participants, compared with eighteen in the first study).

Pepler (1959) measured one-dimension, pursuit tracking during the first half of a one-hour exposure to 21°C T_{db} with 75% rh, and 38° C T_{db} with 65% rh, with an air velocity of 0.5 m/s. Physiological data were not reported. Tracking error was greater during thermal stress, and increased with time on task in the heat.

In an experiment by Beshir, El-Sabagh, and El-Nawawi (1981), six volunteers completed three, thirty-minute blocks of a one-dimension, compensatory tracking task during a two-hour exposure to 20°, 26°, and 30° C WBGT. Thermal physiological data were not reported. Tracking accuracy deteriorated as the environmental temperature increased. Thermal stress exacerbated an increase in tracking error with time on task. The impact of heat on performance was unaffected by variation in the work/rest ratio.

Iampietro et al (1969) measured two-dimension tracking (it is not evident whether the task involved pursuit or compensatory tracking) during a thirty-minute exposure to 24°, 60° and 71° C T_{db}, with 10% rh. The task was performed either in combination with two visual monitoring tasks or with the monitoring tasks and a mental arithmetic task. Rectal and skin temperatures, and heart rate during performance testing were higher in the hot conditions; physiological strain was more marked at 71° than at 60° C T_{db}. However, in spite of the very high dry bulb temperatures, mean rectal temperatures were not substantially elevated, perhaps due to the low relative humidity or the short duration of the exposures (the mean rectal temperature values were 37.4° and 37.5° C at 60° and 71° C T_{db}, respectively). Tracking performance was unaffected at 60° C T_{db} (mean values were not reported). At 71° C T_{db}, error in the horizontal dimension increased when the tracking task was administered in conjunction with the monitoring and arithmetic tasks, but performance was unaffected when the task was completed with the monitoring tasks only.

The studies discussed above are almost entirely consistent in indicating that heat stress impairs tracking. However, the results of an experiment by Nunneley, Dowd, Myhre, Stribley, and McNee (1979) contradict this pattern. Volunteers were exposed for two hours to a control condition of 25° C T_{db}, and to two thermally stressful conditions in which the dry bulb and black globe temperatures were, respectively, 35° and 47°C, and 40° and 52°C. The relative humidity in the stressful conditions was 50%. In the final twenty minutes of the exposures, the participants completed a one-dimension, compensatory tracking task. Three versions of the task were administered in which the task demand was varied by manipulating the bandwidth noise. The most demanding level of the task also incorporated a time lag between control inputs and movement of the cursor. Skin temperature, heart rate, and sweat loss increased in the thermally stressful conditions. Core temperature was slightly elevated in the heat (mean rectal temperatures during the performance testing period at 35° and 40° C T_{db} were 36.9° and 37.3° C, respectively). In the least demanding task, time on target improved as the environmental temperature increased. The more demanding tasks were unaffected by heat stress.

In conclusion, research on the effects of thermal stress on tracking indicates that performance deteriorates in the heat. Impairment of tracking with time on task is exacerbated by thermal stress, and there is some evidence that this effect is more marked with longer exposure to heat. Nunneley et al's observation that heat stress improved the performance of a relatively easy tracking task (Nunneley et al, 1979) is inconsistent with the general pattern of findings. Taken together, the results obtained by Nunneley and her colleagues, and Iampietro et al (1969) suggest that task demand is an important determinant of the impact of heat stress on tracking.

Psychomotor Performance during Heat Stress: Additional Data

Epstein, Keren, Moisseiev, Gasko, and Yachin (1980) administered a target shooting task in the final fifteen minutes of a two-and-a-quarter-hour exposure to 24° C T_{db} with 70% rh, 37°C T_{db} with 50% rh, and 50° C T_{db} with 40% rh. Rectal temperature and heart rate were slightly elevated during exposure to 37° C T_{db} and markedly elevated during exposure to 50° C T_{db}. Error rate increased with environmental temperature. Response times were shorter during exposure to 37° C T_{db} than in either of the other conditions. The statistical significance of these effects was not reported.

Lovingood et al (1967) measured fine and gross motor control of the hand at hourly intervals during a three-and-a-half-hour exposure to 23° and 52 ° C T_{db}. The humidity levels in both conditions were highly variable. Core temperature, heart rate, and sweat loss were significantly elevated in the heat. Fine motor control was enhanced by thermal stress. Gross motor control did not vary between the control and experimental conditions.

The Effects of Heat Stress on Reasoning

Mathematical Reasoning

Research on the effects of heat stress on reasoning has focused almost exclusively on mathematical reasoning. A substantial proportion of this research has obtained negative findings; these can be attributed largely to methodological shortcomings, notably the use of small samples. A number of investigators have reported significant effects of heat stress on arithmetic reasoning, but the pattern of findings is somewhat inconsistent.

Viteles and Smith (1946), and Givoni and Rim (1962) reported that the number of correct computations in multiplication tasks was unaffected by exposure to elevated environmental temperatures. However, the samples tested in these experiments were small; Viteles and Smith tested six individuals and Givoni and Rim tested just four individuals.

Grether et al (1971) measured mental arithmetic during the final thirty minutes of a one-and-a-half-hour exposure to 22° and 50° C T_{db}, with an air velocity of 0.4 m/s. Relative humidity was not controlled. Three additional conditions were included in the experiment: under the control temperature, the participants were exposed during performance testing to (i) 105 dB continuous noise, and to (ii) 5 Hz sinusoidal vibration, and (iii) under the experimental temperature, the participants were exposed to noise and vibration in combination. Rectal and skin temperatures, heart rate and sweat loss were significantly elevated in the heat. No variation in the number of correct computations across the five conditions was evident. As noted previously, the sample used in this study was rather small (ten individuals were tested).

In an experiment by Nunneley, Dowd, Myhre, and Stribley (1978), thirteen volunteers were exposed to two thermally stressful environments of equal dry bulb temperature (35° C) and relative humidity (50%) but different black globe temperatures (35° and 47° C). The participants completed two successive, two-hour exposures to each environment, with an intermediate thirty-minute rest period at 25° C T_{db}. In the final fifteen minutes of each two-hour exposure, the subjects completed several paper-based tests, including an arithmetic task. Rectal and skin temperatures were significantly greater at the higher black globe temperature. The number of correct computations did not vary significantly between the two conditions. Control data were collected from a different sample, which consisted of just six individuals. The environmental conditions in the control exposure were not specified. The mean number of correct computations derived from the combined data for the two stressful conditions was slightly higher than that in the control condition, but this difference was not significant.

Hygge (1991) measured mental addition and subtraction during the first hour of a two-and-a-half-hour exposure to 19° and 27° C T_{db}, with 80-90% rh. Thermal physiological data were not reported. The number of correct computations was unaffected by thermal stress (mean values were not reported).

In a well-controlled experiment, Wilkinson et al (1964) measured performance on an addition task over a period of two hours while oral temperature was maintained at 37.3°, 37.9° or 38.5° C using a specialized clothing assembly. Performance was also measured while oral temperature was maintained at its baseline value. The speed and accuracy of addition were negatively correlated with body temperature. Speed and accuracy were significantly poorer when oral temperature was elevated to 38.5° C compared with performance in the control condition. Performance did not vary with the duration of thermal strain.

Consistent with the results reported by Wilkinson and his colleagues, Iampietro et al (1969) observed a deterioration in the accuracy of mathematical reasoning during exposure to thermal stress. Iampietro and his colleagues measured mental addition and subtraction over the course a thirty-minute exposure to 24°, 60° and 71° C T_{db}, with 10% rh. The arithmetic task was completed simultaneously with two visual monitoring tasks or in conjunction with the monitoring tasks and a tracking task. In spite of the very high dry bulb temperatures, mean rectal temperatures during performance testing were not markedly increased in the heat, perhaps due to the low relative humidity or the short duration of the exposures (the mean rectal temperature values were 37.4° and 37.5° C at 60° and 71° C T_{db}, respectively). At 24° and 60° C T_{db}, there was no significant variation from baseline in the proportion of computations correctly completed (mean values were not reported). At 71° C T_{db}, the proportion of correct computations in each task combination declined from baseline levels. Speed data were not reported.

Contrary to the findings of Wilkinson and his colleagues, Lovingood et al (1967) reported that exposure to thermal stress enhanced the speed of addition. The accuracy of arithmetic reasoning was unaffected by heat stress. These results were replicated by Holland et al (1985), who immersed volunteers in hot water for a period of approximately fifteen minutes to raise the temperature of the external auditory canal to 39° C (skin temperatures were also substantially elevated). In the control condition, the participants were immersed in warm water, which increased skin temperature but did not affect auditory canal temperature. On leaving the water, the participants were dressed in insulative clothing to maintain body temperatures at elevated values and a short battery of performance tasks, including a subtraction task, was administered. Core temperature decreased by approximately 0.3° over the course of performance testing in the experimental condition (skin temperature also decreased during this period, but the magnitude of the decline was not specified).

Mathematical reasoning was faster in the experimental condition. The accuracy of subtraction did not vary significantly between the two conditions.

In summary, research on the effects of thermal stress on arithmetic reasoning has yielded contradictory results. Several experiments have obtained negative findings, but the methodological quality of these studies is generally rather poor. The results obtained by Wilkinson et al (1964) indicate that elevation of body temperature impairs the speed and accuracy of mathematical reasoning. Iampietro et al (1969) also reported that reasoning accuracy deteriorated in the heat. However, Lovingood et al (1967), and Holland et al (1985) observed an improvement in the speed of mathematical reasoning without variation in accuracy. The discrepancy between these two sets of findings is not easily resolved.

Verbal Reasoning

Holland et al (1985) reported that elevation of core and skin temperatures following hot water immersion shortened reaction time in Baddeley's verbal reasoning task. The accuracy of performance was unaffected by thermal strain.

In an experiment by Fine, Cohen, and Crist (1960), volunteers solved anagrams in the first and the penultimate thirty-minute periods of a six-hour exposure to 21° and 35° C T_{db}, with either 30% or 90% rh. In the first thirty minutes of exposure, fewer anagrams were correctly solved in the hot and humid condition. No significant variation in performance across the four conditions was evident during the penultimate thirty minutes of the exposure.

The Effects of Heat Stress on Performance: Miscellaneous Tasks

Visual Coding and Pattern Matching

Mackworth (1950) administered a visual coding task during a three-hour exposure to 29°, 32°, 35°, 38°, and 41° C T_{db}, with 65% rh and an air velocity of 0.5 m/s. Accuracy tended to decline as environmental temperature increased. Accuracy was significantly poorer at dry bulb temperatures of 35°, 38°, and 41° C T_{db} compared with performance at 29° and 32° C T_{db}.

In a subsequent experiment, Pepler (1958) selected the same environmental conditions used by Mackworth, but excluded the hottest condition and reduced the duration of the exposures to one hour and twenty minutes. In the latter half of the exposures, the participants completed a pattern-matching task, which required the comparison of stimulus and reference patterns. The stimulus patterns were presented on a moving display; the time available to compare the stimuli with the reference patterns was varied by altering the speed of the display. At the slowest presentation speed, fewer responses were omitted during exposure to 32° T_{db} than at 29°, 35°, and 38° C T_{db}. At the fastest speed, accuracy was poorer at 35° and 38° C T_{db} than at 29° C T_{db}. Chiles (1958) repeated this experiment, but introduced several changes. The duration of the exposures was reduced to one hour. Chiles also altered the stimuli and presented the patterns at a single speed (which was not used in the original experiment). No significant variation in performance with environmental temperature was observed. The numbers of responses omitted across the conditions were consistent with Pepler's results. Accuracy tended to deteriorate as temperature increased. The failure to reproduce the significant effects observed by Pepler may stem from the differences in experimental design or may be due to the smaller sample used by Chiles (eleven volunteers were tested, compared with twenty-four in the original experiment).

Working and Long Term Memory

Holland et al (1985) reported that elevation of core and skin temperatures following hot water immersion did not affect memory for prose. They tested recall during thermal strain of text learned when body temperatures were at normal values, and recall at normal body temperatures of text learned during thermal strain. Digit span was also unaffected by elevation of body temperatures.

O'Connor (1994) administered the Sternberg memory search task during a two-hour exposure to 24° C T_{db} with 25% rh, and 40° C T_{db} with 70% rh, with an air velocity of 1 m/s. Rectal and skin temperatures, heart rate and sweat loss were significantly elevated in the heat. Reaction time was shorter during thermal strain, without variation in accuracy. In both the control and experimental conditions, the participants employed a serial, exhaustive, memory search strategy.

Occupational Performance

Mackworth (1950) examined the impact of heat stress on military radio operators' decoding of Morse code during a three-hour exposure to 29°, 32°, 35°, 38°, and 41° C T_{db}, with 65% rh and an air velocity of 0.5 m/s. Accuracy tended to deteriorate as the environmental temperature increased. Error rates were significantly higher at dry bulb temperatures of 35°, 38°, and 41° C T_{db} compared with performance at 29° and 32° C T_{db}. Impairment of performance in the heat was more marked in those operators who were judged to be less skilled.

Fine and Kobrick (1978) measured the impact on soldiers' performance of a seven-hour exposure to 21° C T_{db} with 35% rh, and 35° C T_{db} with 90% rh. Thermal physiological data were not reported, but two participants withdrew from the hot condition, suggesting that considerable discomfort was experienced in the heat. At intervals during the exposure, the participants performed a number of operationally relevant tasks, which involved the reception, transcription, and decoding of simulated radio messages. In all of the tasks, error rates were higher during thermal stress. Error rates tended to increase with the duration of the hot exposure.

Froom, Caine, Shochat, and Ribak (1993) investigated the relationship between environmental temperature and the incidence of helicopter accidents attributed to pilot error in the Israeli military services. They reported that mean ambient dry bulb temperature and humidity level were significantly higher on those days on which accidents occurred compared with accident-free days. However, it not evident whether the accident-free days were sampled from the same period of the year from which the accident data were selected (i.e. between May and October). Consequently, the findings may be contaminated by factors such as variation in flying activity with the time of year.

The Effects of the Duration of Heat Stress on Performance

Few researchers have investigated explicitly the impact of the duration of thermal stress on performance. The available data are rather inconsistent, reflecting the variation in the performance measures and exposure conditions utilized. Mackworth (1950) observed that a deterioration in visual signal detection rate in the heat was exacerbated during the latter half of a two-hour exposure period. Wilkinson et al (1964) reported that an increase in auditory signal detection rate while oral temperature was elevated for a period of two hours was enhanced by the duration of thermal strain. However, in the same study, a deterioration in mathematical reasoning was unaffected by the duration of heat strain.

Bursill (1958) reported that a deterioration in pursuit tracking performance with time on task in the heat was greater when the duration of the exposure to thermal stress was increased from one hour and forty-five minutes to two hours and forty-five minutes. However, Azer et al (1972) found that an impairment of compensatory tracking with time on task during a two-hour exposure to heat did not vary with the duration of thermal stress.

Provins and Bell (1970) reported that accuracy in a choice reaction task during the first hour of a two-hour testing session was enhanced by thermal stress. Performance in the second hour of the session did not vary with heat stress.

Fine and Kobrick (1978) administered message reception and decoding tasks to soldiers during a seven-hour exposure to a thermally stressful environment. Heat impaired the accuracy of performance. Error rates tended to increase with the duration of thermal stress.

Psychological Performance during Heat Stress: Theoretical Accounts

Much of the published research on performance during thermal stress is exclusively descriptive. Few theoretical accounts of the impact of heat stress on performance have been proposed, and these are poorly elaborated.

Heat Stress and Performance: The Role of Arousal

The most popular theoretical approach in heat stress research relies on classic arousal theory, which proposes that performance change is mediated by variation in arousal, with performance related to arousal in terms of an inverted U function.

In spite of its popularity, the validity of arousal theory as an account of the relationship between heat and performance is unproven. This is largely due to a lack of methodological rigour in the application of arousal theory in heat stress research. Typically, arousal theory has been used to describe rather than to predict the effects of heat on performance (e.g. Wilkinson et al, 1964; Provins and Bell, 1970; Ramsey and Pai, 1975). By virtue of the inverted U relationship between arousal and performance, the theory can accommodate diverse patterns of results, particularly when ill-defined variables such as task demand are invoked *post hoc* (e.g. Provins and Bell, 1970).

A series of experiments conducted by Poulton and his colleagues used an arousal theory framework to investigate the individual and combined effects of heat and other stressors on performance (Poulton et al, 1974; Poulton and Edwards, 1974a, b). The impact of thermal stress on arousal was inferred *post hoc* from its effects on performance; no collateral evidence of arousal change in the heat was obtained. Poulton et al (1974) reported that exposure to heat stress in combination with loss of a night's sleep produced a smaller deterioration in signal detection rate in an auditory vigilance task compared with either heat or sleep loss alone. The authors interpreted this as indicating that the effects of the two stresses on arousal were antagonistic; thus, heat stress must increase arousal because, by definition, sleep deprivation reduces arousal. However, Poulton and Edwards (1974b) subsequently proposed that the effect of heat *alone* on arousal in combined stressor experiments might be influenced by the nature of the other independent variable. This remarkable suggestion was based on the observation that heat alone impaired tracking in an experiment on the effects of heat and noise (Poulton and Edwards, 1974a), but improved tracking in a study of the effects of heat and l-hyoscine hydrobromide (Poulton and Edwards, 1974b) (the same environmental conditions were used in both experiments). The authors failed to address the implications for their proposal of the observations that heat alone impaired tracking in both the sleep deprivation and noise experiments, and that the effect of heat alone on serial reaction accuracy was consistent across the sleep deprivation, noise, and hyoscine studies. As discussed previously, these experiments utilized a repeated-measures design that was not balanced for first-order carry-over effects. It is conceivable that this flaw underlies the inconsistent effects of heat on tracking observed in the noise and hyoscine studies.

In spite its flexibility, arousal theory cannot account for a number of the findings of research on the combined effects of heat and other stressors on performance. Bell (1978) administered a primary, pursuit rotor task and a secondary, auditory monitoring task during exposures to 22°, 29°, and 35° C T_{db}, with 40-50% rh, in combination with either 55 dB 'background noise' or 95 dB white noise (noise is purported to increase arousal). Individually, both heat and noise increased monitoring error. In combination, the effects of heat and noise on error were additive, which suggests that heat increases arousal. However, the results of an experiment conducted by Hygge (1991) contradicted Bell's findings. Volunteers were exposed to 19° and 27° C T_{db}, with 80-90% rh, in combination with either 38 or 53 dBA ventilation noise. Heat and noise individually impaired performance on a visual search task, but the combined effects of the stressors were antagonistic, which Hygge interpreted as evidence that heat lowers arousal. Similarly, Pepler's observation that both heat and sleep deprivation individually impaired tracking and serial reaction accuracy, but did not have any interactive effects on performance (Pepler, 1959) is difficult to accommodate within an arousal framework.

Few researchers have measured the effect of thermal stress on arousal independently of its impact on performance. Holland et al (1985), and Razmjou and Kjellberg (1992) reported that a decline in subjective alertness with the duration of testing was more marked during thermal strain. Anderson, Deuser, and DeNeve (1995) cited an increase in heart rate during exposure to heat stress as evidence of an increase in arousal, but it is probable that this change in cardiac output was thermoregulatory in origin. The lack of collateral evidence of arousal change in the heat has led to largely speculative accounts of the effect of thermal stress on arousal. For example, on the basis of performance data from just three studies, Poulton and Kerslake (1965) proposed that the effect of heat on arousal is dependent on the duration of exposure to thermal stress. Initially, exposure to heat stress increases arousal. When core temperature begins to rise, arousal falls below its baseline level. As body temperature rises still further and the individual becomes uncomfortably hot, arousal is raised above its baseline level until, finally, arousal decreases as the individual approaches collapse. Poulton (1977) subsequently formulated a quite different account of the impact of the duration of heat stress on arousal, but he did not cite evidence for his proposal. Again, initial exposure to heat raises arousal. If core body temperature is increased by the thermal stress, arousal will remain elevated, but if core temperature is unaffected, arousal will decline below its baseline level.

Arousal theory remains largely untested as an account of performance in the heat, primarily because of the absence of methodological rigour in its application in thermal stress research. This lack of rigour aside, classic arousal theory is flawed in a number of respects. It has proved difficult to define and measure arousal unequivocally (Eysenck, 1982). Hockey (1986) argued that the concept of arousal as a unitary construct, which is implicit in the inverted U model, is excessively simplistic. Eysenck (1982) noted that arousal theory is uninformative about the mechanisms underlying performance change during stress.

The Easterbrook Hypothesis: Dual-Task Performance during Heat Stress

Easterbrook (1959) proposed that the effects of arousal on performance are mediated by changes in attention. Specifically, elevation of arousal increases attentional selectivity. Moderate elevation of arousal enhances performance because attention to peripheral stimuli is reduced. At high levels of arousal, performance is impaired because attention to task-relevant cues is compromised.

The classic methodology for investigating the effects of stress on attentional selectivity involves measurement of dual-task performance. However, as Eysenck (1982) noted, several patterns of dual-task performance are consistent with the Easterbrook hypothesis, which makes validation of the theory difficult. The only patterns that contradict the hypothesis are a greater improvement or a lesser deterioration in performance of the secondary task compared with performance of the primary task.

A number of experiments have investigated the effects of thermal stress on dual-task performance. These studies have yielded largely inconsistent results, reflecting the considerable variation in the exposure conditions and the performance measures utilized.

Bursill (1958) described three experiments in which the participants performed a primary, pursuit tracking task and simultaneously detected lights arranged at 20°, 50°, and 80° eccentricities from the centre of the visual field during exposure to 21° and 41° C T_{db} with 60% rh, with an air velocity of 0.6 m/s. The duration of the exposures was one hour and forty-five minutes in the first experiment and two hours and forty-five minutes in the second. In both experiments, performance was measured during the final forty-five minutes of the exposures. Thermal stress impaired tracking accuracy. Time on target deteriorated more with time on task in the longer than in the shorter heat exposure. Fewer lights were detected in the heat. Detection rate was lower in the longer than in the shorter exposure to heat. Detection rate declined as the eccentricity of the lights increased. This effect was exacerbated by heat stress and by increased duration of the exposure to heat. The third experiment repeated the conditions of the first, but the tracking task demand was reduced by decreasing the frequency of movement of the target. Performance on both tasks was unaffected by heat stress.

Bursill concluded that these results provided evidence of a narrowing of attention under thermal stress. The absence of performance change in the third experiment was interpreted as indicating that the effects observed in the first two studies were central rather than ocular in origin. However, this interpretation is questionable. The negative findings of the third study may stem from the use of a substantially smaller sample than those utilized in the previous experiments (six participants were tested, compared with eighteen in the first and second studies).

In a study by Provins and Bell (1970), volunteers completed a primary, five-choice reaction task and simultaneously detected lights at 29°, 58°, and 87° eccentricities from the centre of the visual field. Two rates of stimulus presentation were used in the reaction task. Performance was measured during the second and third hours of a three-hour exposure to a control and a thermally stressful condition (the environmental conditions were similar to those used by Bursill). Accuracy on the faster paced reaction task during the first hour of performance testing was higher in the heat. The error rate on the slower paced task was too low to be analysed. More lights were detected during heat stress, but the statistical significance of this effect was not reported. The authors proposed that the inconsistency between their results and those obtained by Bursill was due to the greater demand imposed by Bursill's tasks. It is notable that the two sets of findings are incompatible with each other, but neither is inconsistent with the Easterbrook hypothesis.

Bell (1978) administered a primary, pursuit rotor task in conjunction with a secondary, auditory monitoring task in the latter half of a thirty-minute exposure to 22°, 29°, and 35° C T_{db}, with 40-50% rh. Time on target tended to decline as environmental temperature increased, but this effect was not statistically significant. The monitoring task required the participants to indicate whether each of a series of numbers was lesser or greater than the preceding number. Error rate was higher at 35° than at 22° C T_{db}. Reaction time data were not reported.

The results of a study by Azer et al (1972) suggest that thermal stress may impair attentional selectivity: heat impaired performance on a primary tracking task and tended to enhance peripheral visual detection. Independent groups of seven volunteers completed a two-hour exposure to a control environment (24° C T_{db} with 50% rh) and one of three thermally stressful environments (35° C T_{db} with either 50% or 75% rh, and 38° C T_{db} with 50% rh, with and air velocity of 0.2 m/s). The participants completed a primary, compensatory tracking task and simultaneously detected lights at 20°, 60°, and 80° eccentricities from the centre of the visual field. Compared with the control condition, tracking accuracy was poorer in each of the experimental conditions, but this difference was significant only in the hottest environment. The number of lights detected tended to be greater in the hottest than in the control condition, but this difference was not statistically significant. Detection rate was unaffected by the eccentricities of the lights.

The results of this experiment must be interpreted cautiously, as the sample tested was rather small. The findings are indicative of an increase in distractibility in the heat. Eysenck (1982) proposed that narrowing of attention during stress might be an active coping strategy rather than an automatic, passive process as conceived by Easterbrook. On this basis, increased attentional selectivity may be a possible rather than an inevitable concomitant of raised arousal.

Heat Stress and Performance: The Role of Body Temperature

The relationship between body temperature and psychological performance during thermal stress is largely unexplored, primarily because of the dearth of thermal physiological data in the performance literature. Even when physiological data have been measured, few investigators have explicitly examined the relationship between body temperature and performance. Mackworth (1950), and Pepler (1958) reported that there was no association between rectal temperature and several cognitive and psychomotor functions during exposure to thermal stress. Razmjou and Kjellberg (1992) found no significant covariation between rectal temperature and either simple or choice reaction time in the heat. However, Wilkinson et al (1964) reported that oral temperature was negatively correlated with the speed and accuracy of mathematical reasoning, and positively correlated with signal detection rate and the speed of reactions to signals in an auditory vigilance task.

Differential Effects of Core and Skin Temperatures on Psychological Performance

Allnutt and Allan (1973) proposed that elevation of core body temperature increases the speed of psychological performance whereas elevation of skin temperature impairs accuracy. The theoretical basis for this proposal was not made explicit. A series of experiments by Allan and his colleagues sought but ultimately failed to test the hypothesis that core and skin temperature determines the speed and accuracy of performance, respectively. Given the aim of these experiments, the researchers' almost exclusive use of a pursuit rotor task to measure performance was a significant shortcoming, as the task provided a measure of accuracy only.

The experiments conducted by Allan and his colleagues sought to compare performance when the temperature of the auditory canal was maintained at a specific, elevated value, and skin temperature was at either a normal or elevated value. Core temperature was raised by exercise and was maintained at the desired value using a liquid conditioned suit perfused with hot water. Following performance measurement, the temperature of the water was lowered. The performance measures were repeated when skin temperature had returned to a normal value but core temperature was still elevated.

Allan, Gibson, and Green (1979) investigated the effects of elevation of core temperature in combination with either elevated or normal skin temperature on the performance of Baddeley's verbal reasoning task, the Stroop task, and a pursuit rotor task. However, the values of core temperature observed when skin temperature was either elevated or at a normal value were comparable only during the administration of the verbal reasoning task. The core temperatures recorded during performance of the Stroop task and the pursuit rotor task varied by up to 0.7° C when skin temperature was at either an elevated or a normal value. No significant variation in verbal reasoning reaction time was observed (error rates were too low to be analysed). The speed of performance on the Stroop task and time on target in the pursuit rotor task were impaired when both core and skin temperatures were elevated.

Allan and Gibson (1979) measured pursuit rotor performance when core temperature was elevated to 37.9°, 38.2°, and 38.5° C, and skin temperature was either elevated or at a normal value. Performance did not vary significantly with the value of core temperature. Time on target was impaired when skin temperatures were raised. Gibson and Allan (1979) repeated this experiment at lower core temperatures (37.0°, 37.3°, and 37.6° C); the magnitude of the elevation in skin temperature was also less than that in the previous study. No significant variation in pursuit rotor performance was observed.

One of the weaknesses of the experiments described above is that the value of skin temperature was confounded with the direction of change in both skin and core temperatures. In recognition of this, Gibson, Redman, and Allan (1980) measured pursuit rotor performance when core temperature was increasing, at a plateau or decreasing, and skin temperature was either increasing or decreasing. Mean core temperature was close to 38° C during all the performance measurement periods. No significant variation in performance was evident. The failure to observe results consistent with Allan and Gibson's (1979) observation of poorer pursuit rotor performance when both skin and core temperatures were elevated is not readily explicable.

Conclusions

Research on the impact of thermal stress on psychological performance has yielded a largely inconsistent pattern of findings. Few theoretical accounts of the relationship between heat stress and performance have been proposed, and these are poorly elaborated.

The inconsistent pattern of results in the literature is largely attributable to a number of methodological shortcomings in the research, including the use of small samples and, in some instances, flawed experimental design. However, the most significant weakness in previous research is that the independent variable has typically been defined in terms of environmental thermal stress rather than physiological thermal strain. The core body temperature response to thermal stress is affected by the intensity and duration of the stress, and by individual differences in acclimatisation and body size. Defining the independent variable in terms of thermal stress allows significant variation in the degree of thermal strain experienced by experimental participants, not only across experiments, but also between individuals in a single study, and within individuals through the course of heat exposure. Recognition of this source of error in previous experimentation served as the impetus for the research programme described in this dissertation.

The general aim of the research programme was to elucidate the effects of heat on psychological performance. The initial goal was to investigate the effects of precisely controlled thermal strain on a comprehensive range of performance tasks. The objective of the first experiment was to measure performance while core body temperature was maintained at a constant, elevated value. An innovative warm water immersion technique was developed to control core temperature. This technique ensured that inter-individual and temporal variation in thermal strain during performance assessment was minimal, thereby allowing the most significant source of error in previous research to be controlled. The immersion technique and a number of additional methodological issues are discussed in Chapter 3.

CHAPTER 3

Methodological Issues

Controlling Core Temperature

The aim of the first experiment was to examine the effects of precisely controlled thermal strain on psychological performance. Specifically, the experiment sought to measure performance while core body temperature was maintained at a constant, elevated value. This necessitated exposing volunteers to a thermal stress that could be manipulated to allow accurate control of body temperature.

Three sources of thermal stress are commonly utilized in research, either singly or in combination: exercise, specialised clothing, and, most frequently, manipulation of the environmental conditions. The use of exercise to induce thermal strain inevitably affects other variables such as arousal and fatigue, which complicates the design of the control condition. For this reason, exercise was rejected as a means of manipulating heat strain. Several investigators have used specialised clothing to manipulate thermal strain. For example, Wilkinson et al (1964) used an impermeable suit with forced air ventilation to maintain oral temperature at specific, elevated values. However, the utility of specialised clothing in controlling heat strain is restricted by the difficulty of identifying suitable garments, particularly given the omission of relevant clothing details from published research. Manipulation of air temperature was considered unlikely to allow precise control of thermal strain, primarily because the low conductivity of air results in a significant lag in the core temperature response to variations in air temperature. However, the relatively high conductivity of water (which is twenty-five times greater than that of air) could, in principle, allow precise control of core temperature by means of water immersion. In addition, water immersion restricts sweating (a phenomenon termed hydromeiosis), and produces uniform trunk and limb skin temperatures, further enhancing the control of thermal strain.

The Water Immersion Technique

The water temperature manipulations required to control core temperature were explored initially by mathematical modelling using the Wissler model of thermoregulation (Wissler, 1985; the modelling was conducted by the Statistics and Mathematical Modelling section of the Centre for Human Sciences). The aims were to elevate core temperature to 38.5° C and to maintain it at this value for approximately forty-five minutes to allow sufficient time for the administration of a range of performance tasks. This core temperature value is the maximum permitted by local ethics regulations for experimentation with inexperienced volunteers. Elevation of core temperature to 39° C is permitted in volunteers who have experienced experimental elevation of core temperature to 38.5° C on at least two occasions. As the volunteers would be sedentary during water immersion, it was assumed that the mean metabolic rate of the participants would be 100 W/h.

The predictions derived from modelling were tested by conducting pilot immersions with two volunteers. Immersion took place in a large Jacuzzi bath with a capacity of two cubic metres. The water was heated under thermostatic control using an integral heater. Rapid reduction of the water temperature was achieved by adding cold water. The stirring of the water produced by the Jacuzzi jets ensured consistency of temperature throughout the body of water. Water temperature was measured using a thermometer (Gallenkamp AutoTherm, Fisons plc.).

The volunteers were tested individually, lying immersed to the shoulders in a supine position. Core body temperature was operationally defined as rectal temperature, and was measured with a rectal thermistor (Type UU, Grant Instruments Ltd.) inserted 15 cm beyond the anal margin. Skin temperature was measured using skin thermistors (Type UU, Grant Instruments Ltd.) at three sites: the chest, back, and thigh. Body temperatures were recorded using a data logger (1200 series Squirrel, Grant Instruments Ltd.). Heart rate was measured using three Ag/AgCl ECG electrodes, and was displayed on an ECG monitor.

Consistent with the predictions derived from modelling, immersion in water at a temperature of 38.5° C produced a rapid rise in rectal temperature from its baseline value to 38° C in approximately thirty minutes. Water temperature was then lowered to 37.5° C; rectal temperature continued to rise, reaching 38.5° C after approximately twenty minutes, and remaining within ± 0.2° C of this value for a further forty-five minutes. Skin temperatures were typically within ± 0.2° C of water temperature, rising from baseline values of approximately 35° C on the trunk and 33° C on the thigh. The volunteers reported considerable thermal discomfort during elevation of body temperatures.

As the goal rectal temperature of 38.5° C had been exceeded by up to 0.2° C during the pilot immersions, a rectal temperature value of 38.3° C was selected for the performance experiment to avoid breaching ethical limits in inexperienced volunteers. The manipulations of water temperature necessary to maintain core temperature at this value were identified by further mathematical modelling, and were subsequently confirmed in three immersions. The volunteers were initially immersed in water at a temperature of 38.5° C, as before. When rectal temperature reached 38.15° C (approximately forty minutes after initial immersion), the water temperature was lowered to 37.4° C. Approximately ten minutes later, rectal temperature reached 38.3° C, remaining within ± 0.2° C of this level for approximately forty-five minutes. To control this slight variation in rectal temperature in the performance experiment the water temperature was varied by 0.1° C for each deviation of 0.2° C from the goal rectal temperature.

The pilot immersions revealed that the core temperature response to warm water immersion was influenced by variation in body composition, particularly the proportion of body fat. The rate of rise in core temperature during the initial period of immersion tended to be smaller in those volunteers with a greater proportion of body fat (i.e. a mean weighted skin fold thickness exceeding 11 mm). Precise body composition data were not used as a criterion for selecting participants for the performance experiment, but relatively slim volunteers were invited to participate.

The control condition for the performance experiment was provided by immersion in water at a temperature of 35° C. A pilot immersion of one volunteer in water at this temperature for a period of one hour and forty-five minutes produced no change in the baseline value of rectal temperature. Skin temperatures were within ± 0.2° C of the temperature of the water, and subjective thermal comfort was maintained.

In summary, the water immersion technique allowed core temperature to be elevated to and maintained at a specific value for a period of approximately forty-five minutes. This ensured that a range of psychological performance measures could be administered while thermal strain was precisely controlled. The duration of immersion required to raise core temperature to the desired value was affected by variation in the size and composition of the body. However, this variation in immersion duration was relatively slight (approximately ten minutes in the pilot immersions).

The Statistical Power of the Performance Experiment

Previous research on the effects of thermal stress on performance has typically utilized small samples. The use of the water immersion technique to control thermal strain imposed practical constraints on the size of the sample that could be used in the performance experiment (it was necessary to test the participants one at a time). A sample of sixteen participants, with repeated measures, was considered the maximum sample that would be practical. Power analysis indicated that, with α and β values set at 0.05 (two-tailed) and 0.2, respectively, the experiment could detect an effect size (d) of 1.06. Cohen (1977) defined a d value of 0.8 as a large effect. To improve the power of the experiment it was decided that the performance data would be analysed using analysis of covariance with baseline measures of performance treated as covariates.

Selection of the Psychological Performance Measures

Previous investigations of performance in the heat have focused on a limited range of psychological functions, primarily reaction time, vigilance, and tracking, and, to a lesser extent, mental reasoning. A key aim of this research programme was to measure the effects of thermal strain on a comprehensive range of psychomotor and cognitive functions. The performance measures were taken from a task battery (provided by the University of Bristol) consisting of a range of tasks that had been shown to be sensitive to the impact of environmental stressors and variation in state. These included measures of reaction time, vigilance, selective attention, verbal reasoning, and working and long term memory.

As it would not be possible to administer the entire task battery in the time available during immersion, a subset of tasks was selected for use in the first experiment. To identify which of the tasks would be most sensitive to performance change during thermal strain the d value for the experiment was converted for each task variable into the minimum difference between control and experimental means that could be detected at eighty percent power in a sample of sixteen volunteers. These values were calculated using repeated-measures performance data from a sample of twenty-four undergraduates (the data were provided by the University of Bristol). It was assumed that the magnitude of the difference in performance during thermal strain was unlikely to exceed ten percent. On this basis, tasks were selected if the minimum detectable difference between means for at least one of the task variables was less than or equal to ten percent. Using this criterion, two memory tasks were excluded from the performance measures selected for the first experiment.

CHAPTER 4

Experiment 1

Introduction

The aim of this experiment was to assess the impact of precisely controlled thermal physiological strain on psychological performance. The focus of the experiment contrasts with that of previous research on performance in the heat, which has typically defined the independent variable in terms of the environmental stress rather than the participants' physiological response to the stress. Specifically, the experiment sought to measure a comprehensive range of psychological functions while core body temperature was maintained at a constant, elevated value. Core temperature was manipulated using the warm water immersion technique described in Chapter 3. This technique ensured that body temperature was consistent both across the participants and throughout performance measurement, thereby controlling a significant source of error in previous research.

Changes in psychological performance during thermal strain may be associated with or indeed mediated by changes in psychological state. To investigate this possibility cortisol secretion and self-reported mood were measured during immersion.

Method

Participants

The participants were sixteen male members of the staff of the Centre for Human Sciences, who volunteered to take part in the study. The participants ranged in age from nineteen to thirty-three years, with a mean age of twenty-four years. Prior to the experiment, each volunteer underwent a medical examination and gave informed, written consent to participate in the study.

Design

A repeated-measures design was used in which each participant completed a control and an experimental test session. In each session, the participant completed a battery of performance tasks twice: once in a thermoneutral environment prior to immersion to obtain baseline data and once during immersion in water. In the control condition, the participant was immersed in water at a temperature of 35° C for a period of one and a half hours during which rectal temperature was maintained within normal bounds. In the experimental condition, the participant was immersed in water initially at a temperature of 38.5° C; the water temperature was subsequently manipulated as described in Chapter 3 to maintain rectal temperature at 38.3° C while the performance tasks were administered. The test sessions took place in the morning (with immersion from 1015 to 1145 h). To identify any effects of the duration of the session on performance one half of the sample completed the tests in a specific order and the remaining participants completed the tasks in the reverse order. There was an interval of one week between each participant's sessions. The order of exposure to the two conditions was balanced across the participants.

Tests and Measures

Physiological Measures

The physiological variables measured were rectal and skin temperatures, heart rate, and salivary cortisol level. Rectal temperature was measured using a rectal thermistor (Type UU, Grant Instruments Ltd.) inserted 15 cm beyond the anal margin. Skin temperature was measured at five sites: the back, chest, thigh, forehead, and cheekbone using skin thermistors (Type UU, Grant Instruments Ltd.). Heart rate was measured using three Ag/AgCl ECG electrodes. Body temperatures and heart rate were recorded at intervals of thirty seconds using two portable data loggers (1200 series Squirrel, Grant Instruments Ltd.).

Saliva samples were collected on four occasions during each test session and were assayed for cortisol. The participant chewed a small piece of plastic laboratory film (Nesco, Nippon Shoji Kaisha Ltd.) to stimulate salivation and spat approximately 10 ml of saliva into a specimen jar.

Psychological Performance Measures

Psychological performance was measured using seven tasks that assessed a range of cognitive functions. With the exception of the Stroop task, the tasks were controlled by an IBM-compatible personal computer. As safety considerations precluded placing a high voltage monitor close to the Jacuzzi bath, the task stimuli were presented on a liquid crystal display (LCD) computer projection panel (Model QA-1150, Sharp Corporation). The LCD panel was illuminated by six 12 V bulbs contained in a wooden box onto which the panel was mounted. The participant responded to the stimuli using a waterproof console connected to the computer.

Simple Reaction Time

Two simple reaction tasks were administered. In both tasks, a box was presented and, after a brief delay, a square was displayed in the centre of the box. The participant was required to press a response button as soon as the square was detected. In one of the tasks, the period between the presentation of the box and the appearance of the square varied between two and ten seconds. In the second task, the duration of this foreperiod was fixed at two seconds. The duration of each task was three minutes. The variable foreperiod task was presented at the beginning and repeated at the end of the task battery to identify any effects of the duration of the session on performance.

Semantic Processing

This sentence verification task was based on that used by Baddeley and Thomson (unpublished, see Baddeley, 1981). A series of sentences (e.g. 'Trout are fish', 'Shoes grow underground') was presented. The participant was required to indicate as rapidly as possible the veracity of each statement by pressing one of two response buttons. The duration of the task was three minutes.

Verbal Reasoning

This reasoning task was devised by Baddeley (1968). In each trial, a pair of letters (either 'A B' or 'B A') was presented in conjunction with a sentence describing the order of the letters (e.g. 'B follows A'). The syntactic complexity of the sentences was varied by presenting them in active or passive voice, and as positive or negative statements. The participant was required to indicate as quickly as possible whether each sentence was a true description of its corresponding letter pair by pressing one of two response buttons. The duration of the task was three minutes.

Vigilance

This task was similar to one described by Smith and Miles (1986). A series of three-digit numbers was displayed at a rate of one hundred per minute. Each number differed from the preceding number by one digit. The signal, a successive repetition of a number, was presented eight times per minute. The participant was required to respond to the presentation of a signal as rapidly as possible by pressing a response button. Smith, Wilson, Glue, and Nutt (1992) reported that a vigilance decrement becomes evident within a few minutes on this task as a result of the high rate of stimulus presentation and the demand imposed on working memory. The duration of the task was three minutes.

Selective Attention

Selective attention was assessed using two choice reaction tasks described by Broadbent, Broadbent, and Jones (1986). The participant was required to identify as quickly as possible a target letter as 'A' or 'B' by pressing one of two response buttons. In the focused attention (known location) task, the target was presented in the centre of the screen in every trial. At the start of each trial, three square crosses were presented in a horizontal line, one in the centre of the screen, and the outside two at either 1.02° or 2.60° from the centre. The crosses were displayed for 500 ms. The target was then presented, and remained until a response was made. In half of the trials, the target was displayed with a pair of 'distractor' stimuli, which were presented in the same position as the outermost warning crosses. The distractor stimuli were identical to each other and were either asterisks, or the letter 'A' or 'B'.

Sixty-four trial types were utilized in the focused attention task, representing all the combinations of the distance of the warning crosses from the centre (near/far), the nature of the distractor stimuli (no distractor stimuli/letters compatible with the target/letters incompatible with the target/asterisks), the compatibility of the stimulus letter with that presented in the previous trial, and the nature of the distractor stimuli in the previous trial. The participant completed ten practice trials at the beginning of the task, followed by three blocks of the sixty-four trial types.

In the categoric search (unknown location) task, the position of the target letter was not known in advance. At the start of each trial, two crosses were presented horizontally on the screen, either 2.04° or 4.20° apart. The target letter was then displayed in the location of one of the crosses. In half of the trials, a distractor digit (1-7) was presented in the location of the second cross. In half of the trials, the lateral position of the target letter was compatible with the laterality of the response required.

Sixty-four trial types were used in the categoric search task, representing all the combinations of the distance of the target from the centre of the screen (near/far), the presence of a distractor digit (absent/present), the presence of a distractor digit in the previous trial, the compatibility of the stimulus letter with that presented in the previous trial, the lateral compatibility of the target and the response, and the lateral compatibility of the target and the response in the previous trial. The task consisted of three blocks of the sixty-four trial types, preceded by ten practice trials.

Broadbent (1988) argued that tasks that measure only global aspects of performance (e.g. overall speed and accuracy) can obscure more subtle changes in cognitive function. The selective attention tasks described above allow the measurement not only of overall speed and accuracy but also specific attentional phenomena. For example, in the focused attention task, the Eriksen effect (Eriksen and Eriksen, 1974) is evident in enhanced performance when distractor letters identical to the target letter are presented near to the target. Amongst the phenomena measured by the categoric search task is the place repetition effect (Tipper and Cranston, 1985), which describes the improvement in performance evident when stimuli are presented in the same position on successive trials. Broadbent and his colleagues described several further measures derived from the two tasks (see Broadbent et al, 1986). A number of these differentiate particular stages of the choice reaction process (e.g. stimulus encoding, response selection). For example, in the categoric search task, the response selection stage is measured by manipulation of the lateral compatibility of the target and the response.

Stroop Task

In this task, which was based on that described by Stroop (1935), the participant was required either to read aloud printed colour names or to identify ink colours (blue, green, red, and yellow). The task consisted of four stimulus conditions in which the participant was required to identify the colour of ink patches, to read colour names printed in an incompatibly coloured ink, to read colour names printed in black ink, and to identify the colour of ink used to print an incompatible colour name. In each stimulus condition, the participant was presented with a card containing one hundred stimuli. The time taken to complete each card was measured using a stopwatch and errors were recorded.

Subjective Measures

Mood

Mood was assessed using the University of Wales Institute of Science and Technology (UWIST) Mood Adjective Checklist (UMACL) (Matthews, Jones, and Chamberlain, 1990). The checklist consists of twenty-nine adjectives against which mood is rated using a four-point scale. The UMACL yields three bipolar mood dimensions: Energetic Arousal, Tense Arousal, and Hedonic Tone, and a unipolar Anger/Frustration dimension.

Thermal Comfort

Subjective thermal comfort was measured using a nine-point rating scale, which ranged from 'unbearably cold' (-4), through 'comfortable' (0), to 'unbearably hot' (4).

<u>Procedure</u>

A few days prior to his first test session, each participant completed a performance practice session (not immersed in water) in which the task battery was completed three times.

The participants were requested to avoid alcohol for twelve hours prior to their test sessions. Only one of the participants smoked tobacco; he typically smoked one or two cigars in the evening and was not asked to refrain from smoking before his test sessions.

On the days of his test sessions, the participant reported at 0830 h to a climate-controlled preparation room. The environmental conditions were maintained at 24° C T_{db}, with 40% rh. Following insertion of the rectal thermistor, the participant was instrumented with the skin thermistors and the ECG electrodes, and he donned a tracksuit. At 0915 h, physiological data recording was started, mood and thermal comfort measurements were made, and a saliva sample was collected. The participant then completed the performance tasks to obtain baseline data; the task battery took approximately thirty-five minutes to complete. One half of the sample completed the tasks in the following order: simple reaction time (variable foreperiod), verbal reasoning, vigilance, simple reaction time (fixed foreperiod), Stroop, focused attention, categoric search, and simple reaction time (variable foreperiod). The remaining participants completed the tasks in the reverse order. The LCD panel on which the task stimuli were displayed was suspended from a frame mounted on a table. The height and angle of the panel were adjustable.

On completion of the baseline performance assessment, the participant transferred to the room containing the Jacuzzi bath. At 1015 h, he doffed his tracksuit and entered the water. The participant lay immersed to the shoulders in a supine position, supported by inflatable cushions and an adjustable footrest. In the experimental condition, performance measurement was started when rectal temperature reached 38.3° C, approximately fifty minutes after initial immersion. In the control immersion, performance testing was started after a similar period. The LCD panel was suspended from a frame above the bath (see Figure 4.1). The response console was positioned on a rack mounted across the bath.

Mood and thermal comfort measurements were made and saliva samples were collected fifteen minutes after immersion, and immediately before and after completion of the performance tasks.

The participants were permitted to drink water *ad libitum* throughout their test sessions.

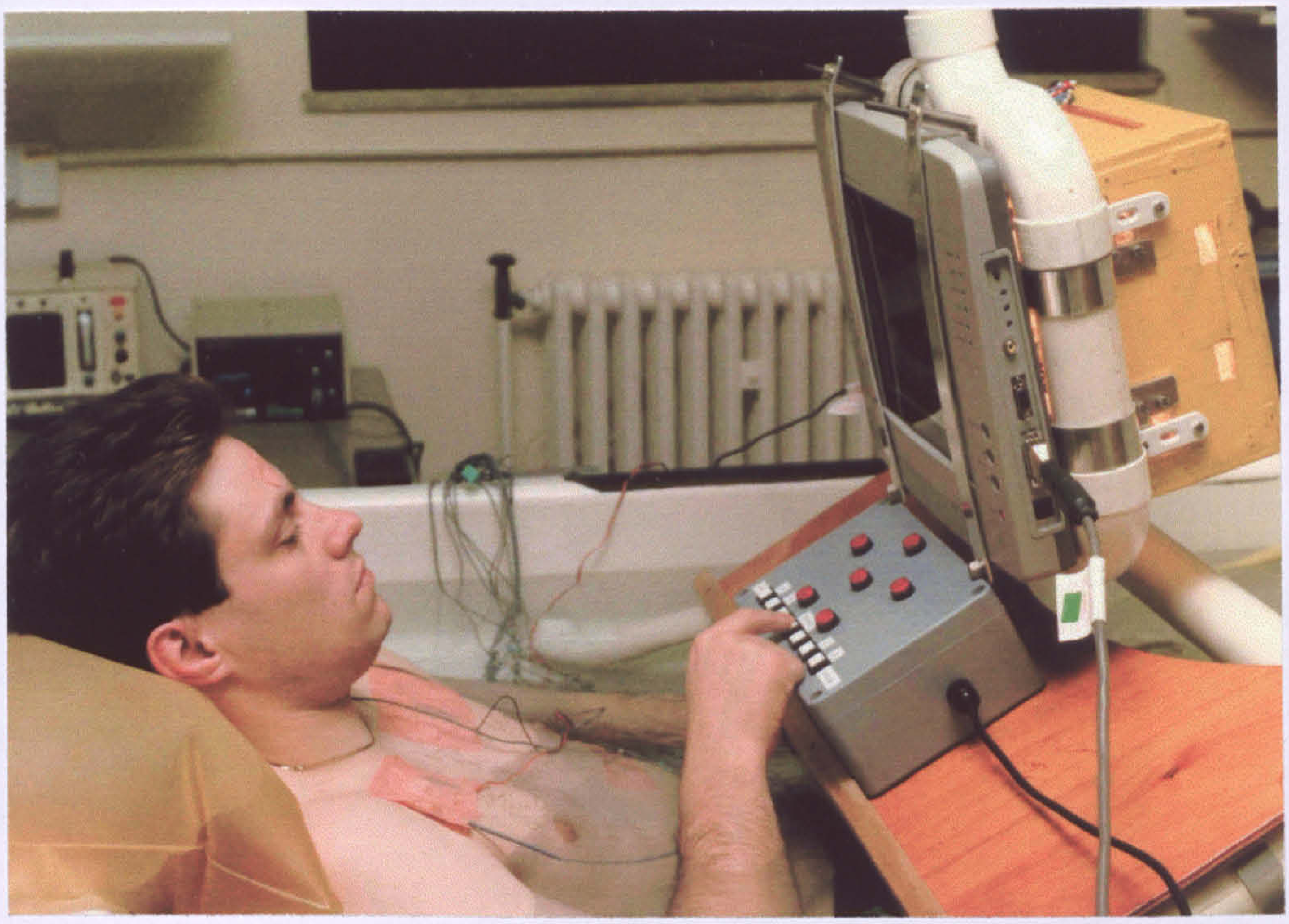

Figure 4.1. Equipment for measuring psychological performance during immersion

Results

Physiological Data

Body Temperatures and Heart Rate

The analysis of the body temperature and heart rate data focused on those periods during which the performance tasks were completed. The principal aim of the analysis was to identify differences in the thermal physiological impact of the control and experimental immersions. The analysis also sought to identify any thermal physiological differences between the baseline period and the control immersion to test the assumption that the latter was a valid control condition. In addition, the data recorded in the ten-minute period prior to immersion were analysed to determine whether there were any differences between the conditions in the participants' physiological state before they entered the water.

The body temperature and heart rate data were analysed using repeated-measures analysis of variance. The independent variables included in the analysis were the condition and the measurement period (i.e. baseline, pre-immersion or immersion). Significant effects revealed by analysis of variance were analysed further using the Newman-Keuls range test and Bonferroni *t* test.

The Thermal Physiological Response to the Experimental Immersion

Rectal temperature, skin temperatures, and heart rate were higher in the experimental than the control immersion ($p < 0.001$ for all variables; see Tables 4.1 and 4.2). The mean rectal temperature observed in the experimental immersion (38.24° C; s.d. = 0.11° C) was slightly lower than the value that had been sought (i.e. 38.30° C).

The principal aim of the experiment was to measure psychological performance while core temperature was maintained at a constant level of elevation. To identify any temporal variation in core temperature during performance testing in the experimental immersion the coefficient of change in rectal temperature was calculated. This revealed a significant but slight mean decrease in rectal temperature through the course of the performance measurement period (-0.0006° C per minute or approximately -0.02° C overall; $p < 0.05$). Skin temperatures and heart rate did not vary significantly during performance testing.

The Thermal Physiological Response to the Control Immersion

In the control test session, there was no significant difference in mean rectal temperature between the baseline period and immersion. This indicated that the control immersion did not cause a significant change in core temperature compared with the values recorded in a thermoneutral air environment.

It was expected that a slight increase in rectal temperature from its baseline level would be evident in the control immersion due to the normal circadian increase in core temperature over the course of the morning. Rectal temperature typically rises by approximately 0.1° C from 0900 to 1200 h (Houdas and Ring, 1982). However, mean rectal temperature was slightly lower during the control immersion than during the baseline period (see Table 4.1). The absence of a rise in rectal temperature may have stemmed from a reduction in metabolic rate due to the relative inactivity of the participants during the experiment. A similar lack of circadian variation in rectal temperature was observed by O'Connor (1994) when sedentary volunteers were exposed from 1000 to 1200 h to 24° C T_{db}, with 25% rh and an air velocity of 1 m/s. Alternatively, the absence of an increase in core temperature may have been due to a redistribution of the body's heat associated with peripheral vasodilatation, caused by the increase in skin temperatures during the control immersion.

Skin temperatures were higher during the control immersion than during the baseline period ($p < 0.001$ for all sites; see Table 4.1). This increase in cutaneous temperature was not indicative of thermal strain, but reflected the impact of the water temperature of 35° C, which was higher than the skin temperatures typically observed in a thermoneutral air environment. Scrutiny of the thermal comfort ratings indicated that comfort was maintained during the control immersion (see Table 4.5).

There was no significant difference in heart rate between the baseline period and immersion.

Rectal and skin temperatures, and heart rate did not vary significantly over the course of performance testing in the control immersion.

The Baseline and Pre-immersion Periods

There were no significant differences between the control and experimental sessions in body temperatures or heart rate during either the baseline or pre-immersion periods.

Salivary Cortisol

The salivary cortisol data were analysed using repeated-measures analysis of covariance, with the baseline measure treated as a covariate. The data were transformed to meet the assumptions of parametric testing. The independent variables included in the analysis were the condition, the time at which the saliva samples were collected, and the order of exposure to the two conditions. Mean cortisol values are shown in Table 4.3; the means have been adjusted on the basis of baseline values, and back-transformed and corrected for bias.

There were no significant main effects of the independent variables on cortisol concentration. Cortisol level was affected by an interaction between the condition, the order of exposure to the conditions, and the time at which the saliva samples were collected ($F = 4.66$, $df = 2, 26$, $p < 0.05$). Further analysis using the Newman-Keuls range test indicated that this interaction reflected a difference in the effect of the time at which cortisol level was sampled between the participants' first and second immersions, irrespective of the condition.

	Control Session	Experimental Session
Rectal Temperature (° C)		
Baseline	36.96 (0.21)	37.02 (0.29)
Pre-Immersion	36.84 (0.21)	36.90 (0.29)
Immersion	36.84 (0.22)	38.24 (0.11)
Back Skin Temperature (° C)		
Baseline	33.83 (1.01)	33.81 (0.86)
Pre-Immersion	33.86 (0.98)	33.81 (0.91)
Immersion	35.25 (0.39)	37.61 (0.12)
Chest Skin Temperature (° C)		
Baseline	34.17 (0.90)	33.96 (0.78)
Pre-Immersion	33.93 (1.11)	33.90 (0.60)
Immersion	35.29 (0.12)	37.70 (0.11)

continued

Table 4.1. Mean core and skin temperatures (° C) during baseline and immersed performance testing, and in the pre-immersion period. Standard deviations are shown in parentheses

	Control Session	Experimental Session
Thigh Skin Temperature (° C)		
Baseline	32.22 (1.14)	32.14 (1.22)
Pre-Immersion	32.27 (1.32)	32.18 (1.15)
Immersion	35.31 (0.10)	37.73 (0.11)
Forehead Skin Temperature (° C)		
Baseline	34.79 (0.67)	34.85 (0.54)
Pre-Immersion	34.51 (0.36)	34.55 (0.39)
Immersion	35.22 (0.43)	37.12 (0.22)
Cheek Skin Temperature (° C)		
Baseline	33.81 (0.99)	33.80 (0.78)
Pre-Immersion	33.44 (0.89)	33.57 (0.77)
Immersion	34.59 (0.73)	37.21 (0.32)

Table 4.1. (continued). Mean core and skin temperatures (° C) during baseline and immersed performance testing, and in the pre-immersion period. Standard deviations are shown in parentheses

	Control Session	Experimental Session
Baseline	67 (15)	71 (11)
Pre-Immersion	75 (14)	77 (12)
Immersion	71 (13)	99 (14)

Table 4.2. Mean heart rate (beats per minute) during baseline and immersed performance testing, and in the pre-immersion period. Standard deviations are shown in parentheses

	Control Immersion	Experimental Immersion
Initial Immersion	1.1 (1.7)	1.3 (0.9)
Prior to Immersed Performance Assessment	0.7 (1.2)	0.6 (1.0)
After Immersed Performance Assessment	0.8 (1.0)	1.0 (1.9)
Mean	0.9 (1.3)	1.0 (1.3)

Table 4.3. Mean salivary cortisol concentration (nmol/L). Standard deviations are shown in parentheses

Subjective Data

Mood

Scores on the Energetic Arousal, Tense Arousal, Hedonic Tone, and Anger/Frustration scales of the UMACL were analysed using repeated-measures analysis of covariance, with baseline measures treated as covariates. The independent variables included in the analysis were the condition, the time at which mood was measured, and the order of exposure to the two conditions. Where necessary, the mood data were transformed to meet the assumptions of parametric testing. Further analysis of significant effects was conducted using the Newman-Keuls range test and Bonferroni *t* test. The means reported below have been adjusted on the basis of baseline values, and where appropriate, have been back-transformed and corrected for bias.

Energetic Arousal was lower during the experimental than the control immersion ($F = 17.06$, $df = 1, 13$, $p < 0.01$; see Table 4.4). This condition effect interacted with the time at which mood was measured ($F = 3.38$, $df = 2, 28$, $p < 0.05$). Further analysis of this interaction indicated that, in the experimental immersion, arousal was lower immediately before performance assessment than on initial immersion or after performance assessment ($p < 0.05$ for both comparisons). Compared with the control immersion, arousal was lower throughout the experimental immersion ($p < 0.01$ on initial immersion and before performance assessment; $p < 0.05$ after performance assessment).

Tense Arousal, Hedonic Tone, and Anger/Frustration scores were unaffected by the independent variables. Tense Arousal and Anger/Frustration tended to be higher and Hedonic Tone tended to be lower during the experimental immersion (see Table 4.4).

	Control Immersion	Experimental Immersion
Energetic Arousal		
Initial Immersion	21.7 (3.7)	19.8 (3.9)
Prior to Immersed Performance Assessment	21.9 (4.2)	18.3 (3.8)
After Immersed Performance Assessment	21.0 (4.3)	19.5 (4.6)
Mean	21.5 (4.1)	19.2 (4.1)
Tense Arousal		
Initial Immersion	12.9 (3.3)	14.5 (4.5)
Prior to Immersed Performance Assessment	12.9 (3.0)	13.7 (4.7)
After Immersed Performance Assessment	12.3 (3.3)	13.7 (2.9)
Mean	12.7 (3.2)	14.0 (4.0)

continued

Table 4.4. Mean mood scores. Standard deviations are shown in parentheses

	Control Immersion	Experimental Immersion
Hedonic Tone		
Initial Immersion	28.0 (3.2)	27.1 (3.5)
Prior to Immersed Performance Assessment	27.3 (3.2)	27.6 (4.0)
After Immersed Performance Assessment	28.3 (4.0)	25.8 (4.3)
Mean	27.9 (3.5)	26.8 (3.9)
Anger/Frustration		
Initial Immersion	5.7 (1.8)	6.1 (1.8)
Prior to Immersed Performance Assessment	5.7 (1.2)	6.1 (2.2)
After Immersed Performance Assessment	5.7 (1.6)	6.9 (3.7)
Mean	5.7 (1.5)	6.4 (2.6)

Table 4.4. (continued). Mean mood scores. Standard deviations are shown in parentheses

Thermal Comfort

The mean ratings of thermal comfort in the control and experimental test sessions are shown in Table 4.5. These indicate that the participants felt uncomfortably warm during the experimental immersion.

	Control Session	Experimental Session
Baseline	0.4 (0.6)	0.3 (0.4)
Initial Immersion	-0.2 (0.6)	1.3 (0.7)
Prior to Immersed Performance Assessment	-0.1 (0.6)	1.7 (0.9)
After Immersed Performance Assessment	-0.1 (0.6)	1.3 (0.9)

Table 4.5. Mean thermal comfort ratings (a rating of 0 indicates comfort). Standard deviations are shown in parentheses

The Effects of Warm Water Immersion on Thermal Physiological and Psychological State: Summary

The participants experienced substantial thermal strain during the experimental immersion as evidenced by the marked elevation of core temperature, skin temperatures, and heart rate. This physiological strain was accompanied by an increase in thermal discomfort. Temporal variation in core temperature during performance testing in the experimental immersion was slight.

Energetic Arousal was reduced during thermal strain. In addition, heat strain tended to increase Tense Arousal and Anger/Frustration, and to reduce ratings of Hedonic Tone.

Psychological Performance Data

The performance data were analysed using repeated-measures analysis of covariance, with baseline performance treated as a covariate. The independent variables included in the analysis were the condition, the order in which the performance tasks were completed, and the order of exposure to the two conditions. Task variables were included as appropriate. Where necessary, the performance data were transformed to meet the assumptions of parametric analysis. Significant effects were analysed further using the Newman-Keuls range test and Bonferroni *t* test.

Only those results that are pertinent to the focus of the experiment are described below. Psychological performance was affected by several of the independent variables, but only the main effects of heat strain and the interactions of heat strain with other variables are discussed. The means reported have been adjusted on the basis of baseline performance and, where applicable, the means have been back-transformed and corrected for bias. The mean values of the performance variables are shown in Appendix I.

The Effects of Thermal Strain on Performance

The principal effect of heat strain on psychological performance was a generalized increase in the speed of performance. This effect was evident in several of the tasks. Shorter reaction times during heat strain were evident in the fixed foreperiod simple reaction task ($F = 5.25$, $df = 1, 10$, $p < 0.05$; see Figure 4.2), the verbal reasoning task ($F = 5.68$, $df = 1, 11$, $p < 0.05$; see Figure 4.3), and the semantic processing task ($F = 12.46$, $df = 1, 11$, $p < 0.01$; see Figure 4.4). In addition, heat strain reduced overall reaction times in the categoric search task ($F = 8.71$, $df = 1, 10$, $p < 0.05$; see Figure

4.5) and the Stroop task ($F = 6.39$, $df = 1, 8$, $p < 0.05$; see Figure 4.6). The magnitude of the decrease in reaction time in these five tasks ranged from three to seven percent. The reduction in reaction time in the verbal reasoning task was mirrored in an increase in the number of trials completed during heat strain ($F = 24.21$, $df = 1, 11$, $p < 0.001$; the mean values were 56 and 61 trials in the control and experimental immersions, respectively). A similar effect was evident in the semantic processing task ($F = 11.24$, $df = 1, 11$, $p < 0.01$; the mean values were 116 and 126 trials in the control and experimental immersions, respectively).

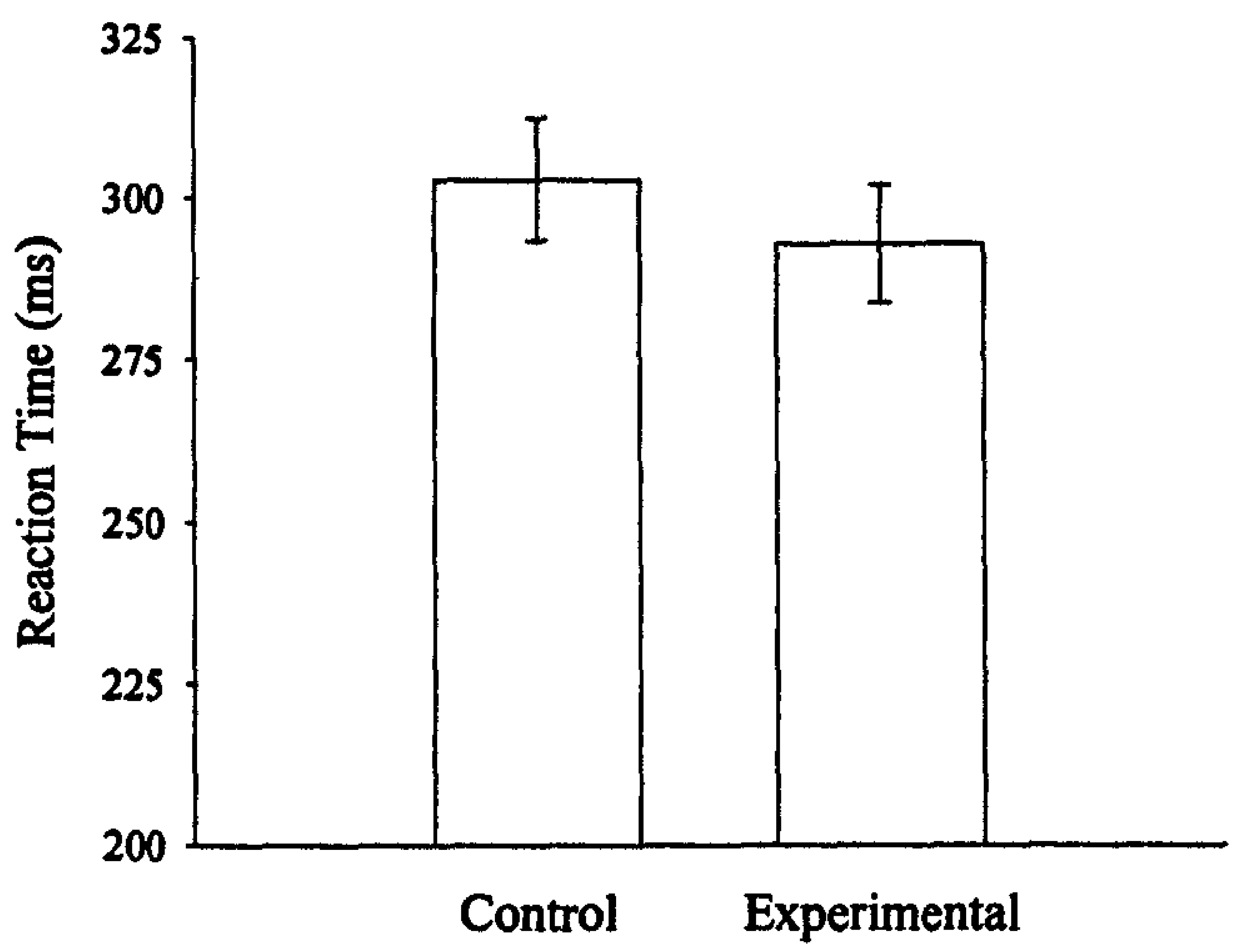

Figure 4.2. Fixed foreperiod simple reaction task: Mean reaction time in the control and experimental immersions. Standard errors of the mean are shown (95% confidence intervals)

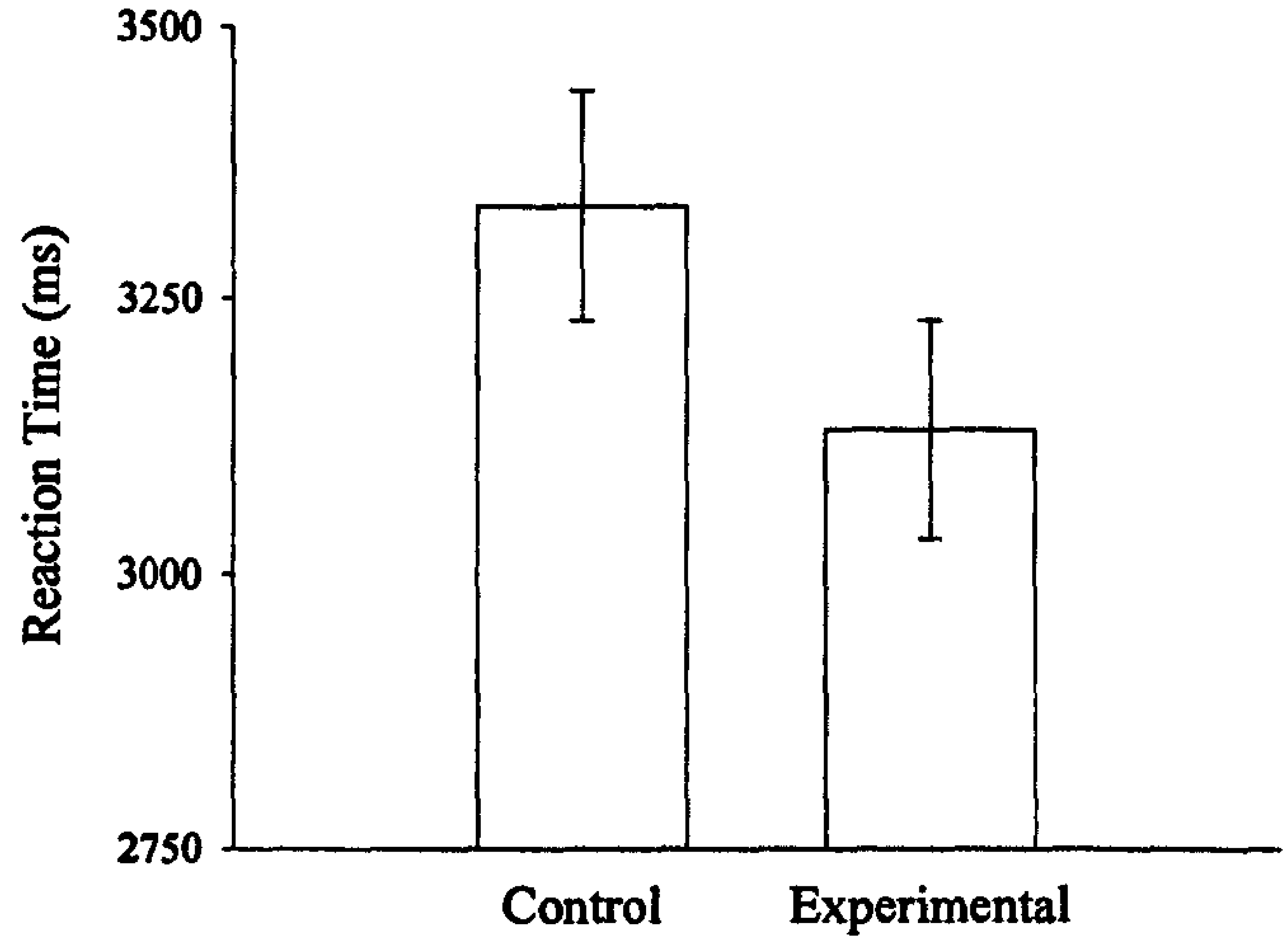

Figure 4.3. Verbal reasoning task: Mean reaction time in the control and experimental immersions. Standard errors of the mean are shown (95% confidence intervals)

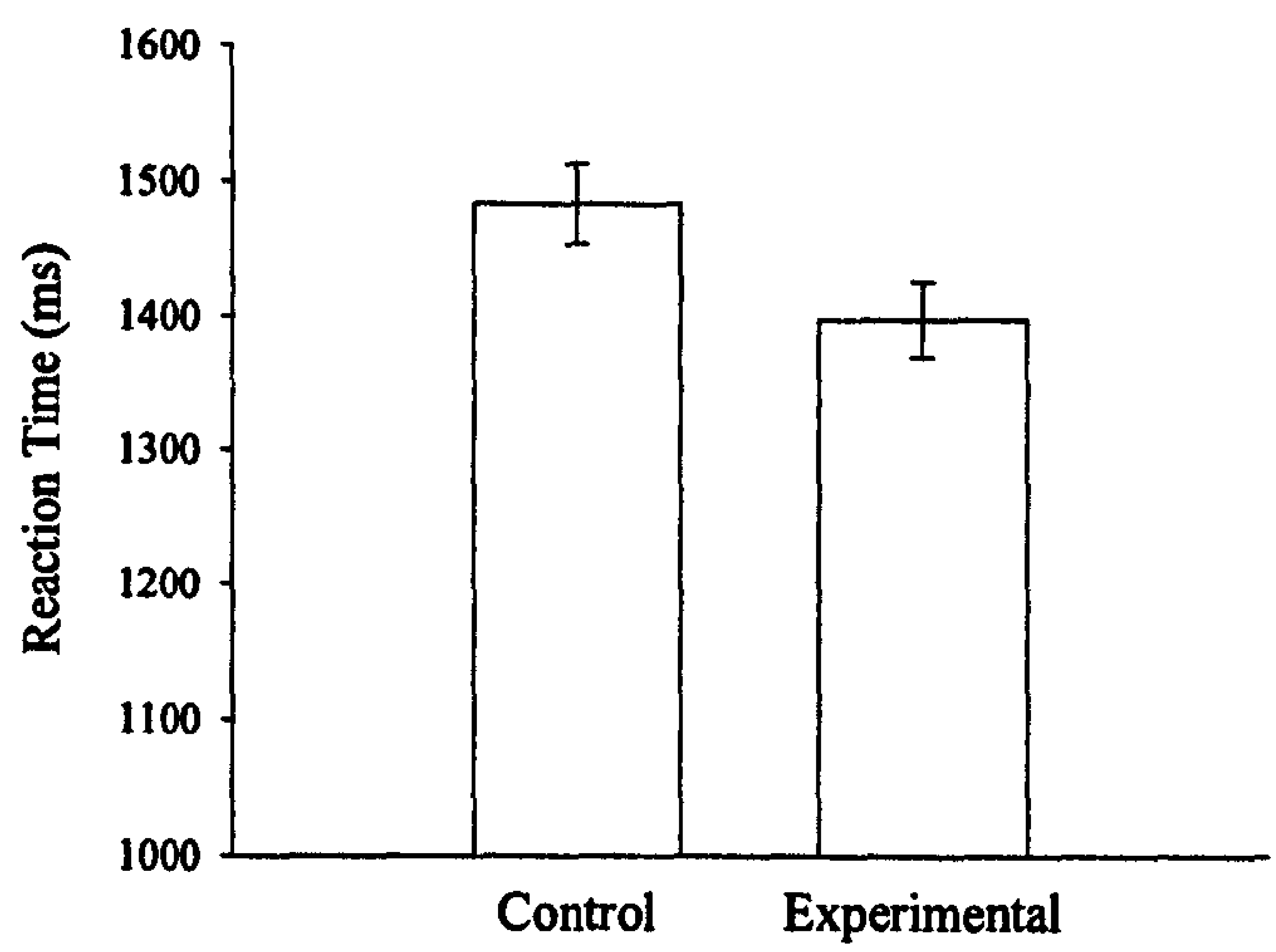

Figure 4.4. Semantic processing task: Mean reaction time in the control and experimental immersions. Standard errors of the mean are shown (95% confidence intervals)

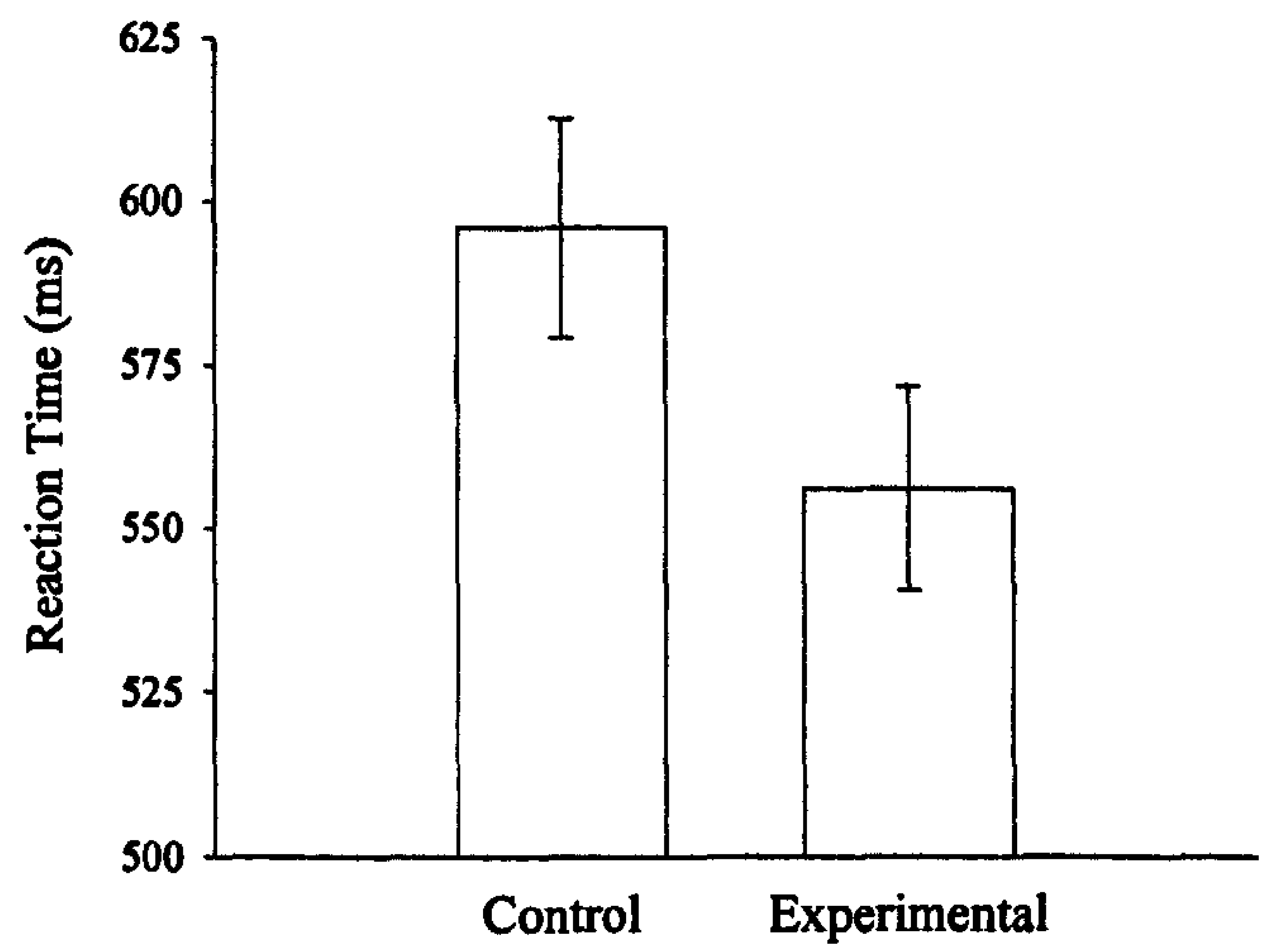

Figure 4.5. Categoric search task: Mean overall reaction time in the control and experimental immersions. Standard errors of the mean are shown (95% confidence intervals)

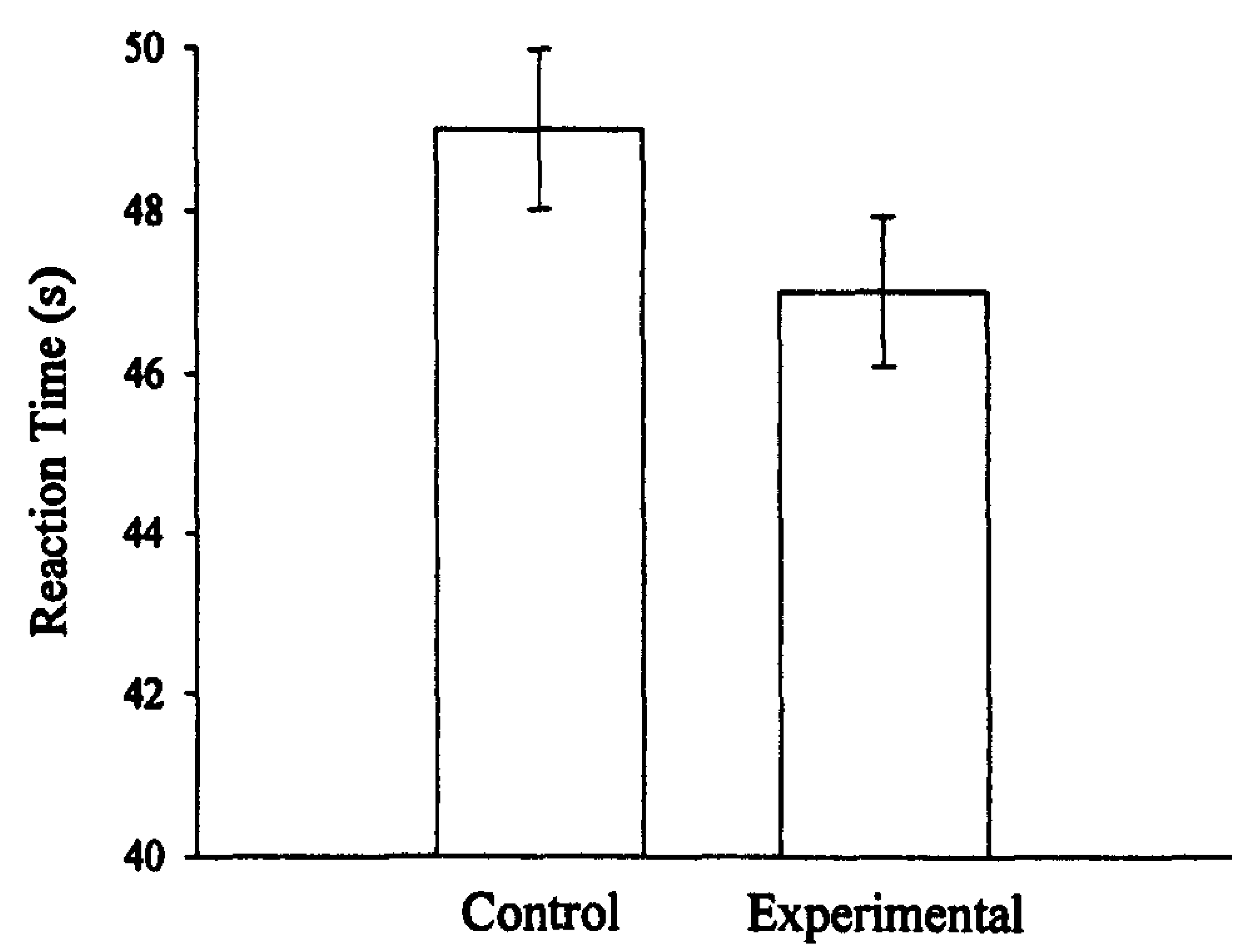

Figure 4.6. Stroop task: Mean overall reaction time in the control and experimental immersions. Standard errors of the mean are shown (95% confidence intervals)

No significant effects of heat strain on reaction time were evident in the variable foreperiod simple reaction task, the vigilance task or the focused attention task. However, scrutiny of the mean reaction times in these tasks indicated that reaction latency tended to be shorter during thermal strain (see Table 4.6). Comparison of performance in the two presentations of the variable foreperiod simple reaction task (the task was presented at the beginning and repeated at the end of the test battery) revealed that the magnitude of the reduction in reaction time during heat strain was greater in the first than in the second presentation of the task (six and two percent, respectively). This suggests that the enhancement of performance speed during thermal strain was attenuated as the duration of the session increased.

	Control Immersion	Experimental Immersion
Simple Reaction Task (variable foreperiod) First presentation	343 (43)	323 (55)
Simple Reaction Task (variable foreperiod) Second presentation	374 (54)	365 (50)
Vigilance Task Reaction time to signals	563 (102)	550 (85)
Focused Attention Task Overall reaction time	479 (84)	456 (73)

Table 4.6. Mean reaction times (ms) in the simple reaction, vigilance, and focused attention tasks. Standard deviations are shown in parentheses

There was no evidence that the reduced reaction times observed during heat strain reflected a trade-off between the speed and accuracy of performance. Performance accuracy did not vary significantly between the control and experimental immersions. Mean accuracy scores are shown in Table 4.7.

	Control Immersion	Experimental Immersion
Semantic Processing Task	93 (4)	92 (4)
Verbal Reasoning Task	82 (19)	80 (18)
Stroop Task	100 (0.5)	100 (0.3)
Categoric Search Task Overall accuracy	97 (2)	97 (3)
Focused Attention Task Overall accuracy	97 (5)	96 (5)

Table 4.7. Mean accuracy scores (% correct) in the semantic processing, verbal reasoning, Stroop, and selective attention tasks. Standard deviations are shown in parentheses

In the vigilance task, signal detection rate was higher during heat strain ($F = 5.94$, $df = 1, 10$, $p < 0.05$). The mean detection rates in the control and experimental immersions were 4.4 and 5.3 signals per minute, respectively. The false detection rate did not differ significantly between the control and experimental immersions (the mean values were 5.1 and 4.9 false positives per minute, respectively). From the perspective of signal detection theory, these results suggest that the improvement in signal detection rate during heat strain reflected an increase in signal detectability rather than a change in the decision criterion.

Some of the variables derived from the categoric search task were affected by thermal strain, but there was little evidence of changes in attention *per se*. The mean reaction time to trials in which the target letter differed from that in the preceding trial was lower during heat strain ($F = 13.67$, $df = 1, 10$, $p < 0.01$; means were 617 and 562 ms in the control and experimental immersions, respectively). This effect was mirrored in a reduction during heat strain in the mean difference in reaction times to trials in which the target letter differed from its predecessor and trials in which the target was repeated in succession ($F = 5.51$, $df = 1, 10$, $p < 0.05$; mean differences were 26 and 6 ms in the control and experimental immersions, respectively). Taken together, these findings indicate that the relative increase in reaction time when target stimuli differed on successive trials was less marked during thermal strain. This suggests that heat strain enhanced the speed of execution of the response choice stage of the reaction process.

Analysis of performance on the Stroop test indicated that the magnitude of the Stroop effect (i.e. the difference between reaction times to the word interference condition and the colour condition, divided by the latter) did not differ significantly between the control and experimental immersions (the mean values were 0.36 and 0.39, respectively).

The Effects of Task Variables on Performance during Thermal Strain

In the verbal reasoning task, reaction time was affected by the syntactic complexity of the stimuli ($F = 12.02$, $df = 3, 35$, $p < 0.001$). This effect varied with thermal strain ($F = 3.33$, $df = 3, 35$, $p < 0.05$; means are shown in Table 4.8). Comparison of the reaction times to each of the four syntactic categories of stimuli in the control and experimental immersions indicated that the mean reaction time to the positive, passive statements was shorter during heat strain ($p < 0.01$). Reaction times to the remaining categories did not vary significantly with thermal strain. In the control immersion, reaction time to the positive, active statements was less than those to the other syntactic categories ($p < 0.001$ for all comparisons). Reaction time to the negative, active statements was less than those to the positive, passive statements ($p < 0.001$) and the negative, passive statements ($p < 0.05$). In the experimental immersion, reaction time to the positive, active statements was less than those to the two passive categories ($p < 0.001$ for both comparisons). Reaction time to negative, active statements was less than to negative, passive statements ($p < 0.01$).

	Control Immersion	Experimental Immersion
Positive, active voice	2644 (466)	2724 (744)
Positive, passive voice	3866 (1043)	3328 (879)
Negative, active voice	3229 (899)	3011 (712)
Negative, passive voice	3605 (1142)	3463 (985)

Table 4.8. Verbal reasoning task: Mean reaction times (ms) for condition and syntactic category of stimuli. Standard deviations are shown in parentheses

The Effects of Time on Task on Performance during Thermal Strain

The data for each one-minute block of the simple reaction and vigilance tasks were analysed to examine the effect of time on task on performance. Performance on the simple reaction tasks did not vary significantly with time on task. In the vigilance task, signal detection rate deteriorated with time on task ($F = 4.87$, $df = 2, 21$, $p < 0.05$), but this effect did not interact with thermal strain.

Additional Sources of Variation in Performance during Thermal Strain

Interaction effects between the condition and the order of exposure to the two conditions were observed in verbal reasoning reaction time ($F = 4.99$, $df = 1, 11$, $p < 0.05$) and in the accuracy of performance in the semantic processing task ($F = 5.59$, $df = 1, 11$, $p < 0.05$). These effects appeared to reflect differences in performance between the participants' first and second test sessions, irrespective of the condition.

Interactions of the condition, the order of exposure to the two conditions, and the order in which the performance tests were presented affected the number of trials completed in the verbal reasoning task ($F = 18.87$, df = 1, 11, $p < 0.01$) and the accuracy of performance in the semantic processing task ($F = 7.79$, df 1, 11, $p < 0.05$). Further analysis indicated that these interaction effects reflected variation in the effect of the order in which the tasks were completed between the participants' first and second test sessions, irrespective of the condition.

Covariation between Subjective Arousal and Psychological Performance during Thermal Strain

To identify any association between subjective arousal and psychological performance during thermal strain the covariation between Energetic Arousal scores and performance was examined. Only those performance variables that had been significantly affected by heat strain were included in this analysis. Correlation coefficients were calculated between the changes in the arousal scores and the performance variables from baseline to immersion (i.e. baseline minus immersed values) in the control and experimental sessions. One coefficient (5% of the total) was statistically significant at a probability of five percent (using a two-tailed test). The change in overall reaction time in the categoric search task from baseline to the experimental immersion was negatively correlated with arousal ($r = -0.53$, $n = 15$, $p < 0.05$). However, this correlation appears spurious, as it contradicts the decrease in both reaction time and Energetic Arousal observed during thermal strain.

The covariation between the remaining mood variables (which had not been affected significantly by heat strain) and performance was also examined. Just six percent of the coefficients were significant (all at a probability of five percent), which suggests that the correlations were not robust. Indeed, scrutiny of the significant coefficients revealed little consistent covariation between mood and performance during heat strain.

Covariation between the Physiological Variables and Performance in the Experimental Immersion

The use of the water immersion technique ensured that body temperature values during performance measurement were consistent across the participants. However, the magnitude of the increase in core and skin temperatures during the experimental immersion varied across the participants due to individual differences in baseline body temperatures. To identify any association between physiological response and psychological performance the covariation between the physiological and performance data was examined. Correlation coefficients were calculated between the changes in the physiological and performance variables from baseline to immersion (i.e. baseline minus immersed values) in the control and experimental sessions. Only those variables that had been significantly affected by thermal stress were included in the analysis. Eleven percent of the coefficients were statistically significant at a probability of five percent or less (using a two-tailed test).

Examination of the significant coefficients yielded some limited evidence that the magnitude of the increase in core temperature was positively associated with the speed of performance during heat strain. The change in rectal temperature was negatively correlated with reaction time in the verbal reasoning task ($r = -0.50$, $n = 15$, $p < 0.05$). A negative correlation was observed between rectal temperature and one of the variables derived from the categoric search task, namely, the difference between reaction times to trials in which the target letter differed from its predecessor and trials in which the target was repeated in succession ($r = -0.52$, $n = 14$, $p < 0.05$). No consistent pattern of association was evident between performance in the experimental immersion and either skin temperatures or heart rate.

Discussion

The aim of this experiment was to measure psychological performance while core body temperature was maintained at a constant level of elevation. The water immersion technique permitted the induction of substantial thermal strain. Core and skin temperatures, and heart rate were significantly elevated in the experimental immersion, and subjective thermal discomfort was increased. The immersion technique also allowed core temperature to be maintained at a constant value with a high degree of precision. Temporal variation in core temperature during performance measurement was slight. In ensuring consistency of thermal strain both across the participants and throughout the performance testing period, the experiment controlled a significant source of error in previous research.

Subjective Energetic Arousal was lower during thermal strain. In addition, heat strain tended to increase Tense Arousal and Anger/Frustration, and to reduce ratings of Hedonic Tone.

The most salient effect of thermal strain on psychological performance was a general decrease in reaction time, without variation in accuracy. Both simple and choice reaction times were shorter during heat strain. Reaction time in the fixed foreperiod simple reaction task and overall reaction time in the categoric search choice reaction task were significantly reduced in the experimental immersion. Reaction time in the variable foreperiod simple reaction task and the focused attention task tended to be shorter during thermal strain, but this variation was not significant.

Previous research on the impact of heat stress on simple reaction time has yielded a contradictory pattern of findings. Consistent with the results of this experiment, Lovingood et al (1967), and Ramsey (1975, cited in Ramsey and Pai, 1975) reported that heat shortened simple reaction time. However, both studies were rather poorly controlled. Razmjou and Kjellberg (1992) observed an increase in simple reaction time during exposure to heat stress. The discrepancy between their results and those of the present experiment may have its origin in the substantially greater degree of thermal strain induced in the present study (mean core temperature was approximately 0.8° C higher than the values observed by Razmjou and his colleague). However, Benor and Shvartz (1971) reported negative results, even during marked thermal strain.

There have been few studies of the effects of thermal stress on choice reaction time and, in general, these have been compromised by methodological flaws. The results of these studies suggest that heat increases reaction time and enhances the accuracy of performance, but these conclusions must be regarded as unproven. In the present experiment, thermal strain shortened choice reaction time, without affecting accuracy. The categoric search choice reaction data yielded some evidence that heat strain increased the speed of execution of the response choice stage of the reaction process.

Enhanced speed of performance was evident in several further tasks. During heat strain, significantly lower reaction times were observed in the semantic processing task and the verbal reasoning task. The latter finding is consistent with the results reported by Holland et al (1985). Overall reaction time in the Stroop task was significantly reduced in the experimental immersion. In the vigilance task, reaction time to signals tended to be shorter during heat strain.

There was no evidence that the decrease in reaction times during thermal strain reflected a trade-off between the speed and accuracy of performance. Performance accuracy was unaffected by heat strain. In the Stroop task, the mean of the error rates in the control and experimental immersions was zero percent. The mean error rates in the categoric search and focused attention tasks were low (three and four percent, respectively). It is possible that the relative ease of these tasks rendered them insensitive to any effect of thermal strain on performance accuracy. However, the mean error rates in the semantic processing and verbal reasoning tasks were substantially greater (eight and nineteen percent, respectively), and this suggests that these tasks would be sensitive to any variation in performance accuracy with thermal strain, but no such effects were observed.

It is possible that the consistent pattern of faster performance without variation in accuracy observed during thermal strain is due, at least in part, to an increase in nerve conduction velocity and the speed of motor responses associated with elevation of body temperature. A number of studies have provided evidence of a positive relationship between body temperature and sensory nerve conduction velocity in homeothermic and poikilothermic animals (e.g. Wheeler, 1989; Ide and Hosaka, 1990). In humans, sensory nerve conduction velocity is similarly influenced by body temperature. For example, Buchtal and Rosenfalk (1966) cooled the tissue adjacent to the median nerve to 18° C. As the temperature returned to its normal value, conduction velocity in the median nerve increased by 2m/s/° C. Stegeman and De Weerd (1982) reported that conduction velocity in the human sural nerve varied with the temperature of the surrounding tissue at a rate of 1.9m/s/° C. A similar study by Trojaborg, Moon, Andersen, and Trojaborg (1992) observed a rate of increase in sural nerve conduction velocity of 1.5m/s/° C. It appears reasonable to assume that the effect of temperature on conduction velocity applies as much to motor nerve conduction as to sensory nerve conduction. Goodman, Hancock, Runnings, and Brown (1984) used a warm water immersion technique to examine the differential effects of elevation of body and arm temperatures, both singly and in combination, on the pre-motor and motor stages of the simple and choice reaction process. The pre-motor stage was largely unaffected by elevation of temperature. The motor stage was shorter only when arm temperature was raised. These findings suggest that much of the enhancement of reaction time during thermal strain is attributable to an increase in the speed of execution of motor responses rather than an increase in the speed of the reception and processing of stimuli. Of course, this may apply only to tasks similar to those used by Goodman and his colleagues (the participants pressed buttons in response to visual stimuli) in which the perception and processing of stimuli accounts for a relatively small proportion of the total reaction time. Furthermore, the results obtained by Goodman and his colleagues must be interpreted cautiously, as just two volunteers were tested. Taken as a whole, the studies outlined above indicate that elevation of body temperature increases nerve conduction velocity and the speed of execution of motor responses. It is conceivable that these effects underlie the enhancement of performance speed observed during thermal strain.

In light of the evidence that elevation of body temperature increases nerve conduction velocity and the speed of motor responses, the absence of a consistent finding of shorter reaction times in previous heat research is not readily explicable. The results obtained by Goodman and his colleagues support a tentative explanation. Previous research has typically exposed participants to elevated air temperatures. This technique may not necessarily result in a significant increase in arm temperature, particularly if the thermal stress is relatively benign or the exposure is relatively short.

In the vigilance task, signal detection rate was higher during thermal strain. The false detection rate did not vary significantly with heat strain, which suggests that the improvement in signal detection reflects an enhancement of signal detectability rather than a reduction in the decision criterion. This pattern of findings is inconsistent with the results of previous studies of the effects of heat stress on vigilance. In general, previous research indicates that heat impairs signal detection, and provides some evidence that this effect is attributable to a decrease in signal detectability (e.g. Benor and Shvartz, 1971). Wilkinson et al (1964) reported that elevation of oral temperature increased signal detection rate in an auditory vigilance task, but in the absence of false detection data, the origin of this improvement cannot be discerned. Colquhoun and Goldman (1972) also observed an increase in signal detection rate in the heat. However, they presented evidence that this effect was due to a reduction in the decision criterion. The novel pattern of results observed in this experiment may reflect the nature of the vigilance task administered. All of the previous studies reviewed employed vigilance tasks that used sensory stimuli (e.g. lights or tones). However, the task utilized in this experiment required the detection of successive repetitions of numbers, and, therefore, can be regarded as a cognitive vigilance task.

In light of the evidence that elevation of body temperature enhances nerve conduction velocity, it is possible that the improvement in signal detectability in the cognitive vigilance task stems from an increase in the speed of information processing. The requirement to detect successive repetitions of stimuli coupled with the high event rate (one hundred events per minute) presented a significant processing demand. In the control immersion, fifty-five percent of the signals were detected. As a signal was composed of two events, the probability of correctly identifying a single event was seventy-four percent (i.e. the square root of the probability of correctly detecting two successive events). During thermal strain, sixty-six percent of the signals were detected; therefore, the probability of correctly identifying a single event was eighty-one percent. The magnitude of the improvement in processing capacity when body temperature was elevated was seven percent. This is similar to the size of the improvement in reaction time observed during thermal strain, which ranged from three percent in the fixed foreperiod simple reaction task to seven percent in the categoric search task. The broad similarity of the magnitude of the two types of temperature-related changes supports the proposal that the improvement in signal detectability reflects faster information processing associated with an increase in neuronal conduction velocity.

There was no evidence that thermal strain affected selective attention. None of the classic attentional phenomena measured by the focused attention and categoric search tasks (e.g. the Eriksen effect; the place repetition effect) varied with heat strain. The magnitude of the Stroop effect was also unaffected by thermal strain.

The effects of thermal strain on performance did not vary significantly with the order in which the performance tests were completed, which suggests that performance during heat strain was unaffected by the duration of the test session. However, comparison of performance in the two presentations of the variable foreperiod task (which was presented at the beginning and repeated at the end of the task battery) indicated that the enhancement of simple reaction time during heat strain was attenuated in the second presentation of the task. It was not possible to discern whether this effect had its origin in the duration of thermal strain or the duration of the performance testing period, as these variables were confounded.

The results of this experiment do not support theoretical accounts of the relationship between heat and performance proposed by previous researchers. The findings are inconsistent with a classic arousal theory account of performance in the heat. Subjective Energetic Arousal was lower in the experimental immersion, but there was little evidence of consistent covariation between arousal and performance during heat strain. There was no consistent association between subjective tension and performance. Subjective arousal is not, of course, necessarily a valid measure of autonomic arousal, but Matthews et al (1990) presented evidence that the UMACL arousal scales are correlated with psychophysiological indices of autonomic arousal.

The results of this study are incompatible with the proposal that elevation of core temperature enhances the speed of performance whereas elevation of skin temperature impairs accuracy (Allnutt and Allan, 1973). Reaction times were shorter during thermal strain, and there was some limited evidence that the magnitude of the increase in rectal temperature in the experimental immersion was positively associated with the speed of performance. However, performance accuracy was unaffected by heat strain, in spite of the marked elevation of skin temperatures.

Conclusions

In measuring psychological performance while core temperature was maintained at a constant level of elevation, this experiment controlled a significant source of error in previous research on performance in the heat. The principal effect of thermal strain on performance was a general decrease in reaction time, without variation in accuracy. It is conceivable that this effect is attributable, at least in part, to an increase in nerve conduction velocity and the speed of motor responses associated with raised body temperature. Signal detection rate in the vigilance task was enhanced by thermal strain. This effect appears to reflect an increase in signal detectability, which may stem from an increase in the speed of information processing when body temperature is elevated. There was no evidence that selective attention was affected by heat strain.

The effects of thermal strain observed in this experiment do not support theoretical accounts of the relationship between heat and psychological performance proposed by previous investigators. Contrary to classic arousal theory, there was little evidence to suggest that the impact of heat strain on performance was mediated by arousal. The results of the experiment contradict the proposal that elevation of skin temperature impairs the accuracy of performance.

Directions for Subsequent Research

On the basis of the results of this experiment, a second water immersion study was proposed. The principal aims of this experiment were to assess whether the effects observed in the first experiment could be replicated and to measure the impact of heat strain on several additional mental functions. Several of the tasks used in the first experiment and a number of additional performance measures were selected for administration in the second experiment.

The first experiment yielded some evidence that the enhancement of reaction time during thermal strain was reduced towards the end of the session. It was not possible to identify whether this effect reflected the impact of the duration of heat strain or the duration of the performance testing period. There is some evidence in the thermal stress literature that performance is affected by the duration of exposure to heat (e.g. Mackworth, 1950; Bursill, 1958; Wilkinson et al, 1964) although a number of investigators have reported negative findings (e.g. Wilkinson et al, 1964; Azer et al, 1972). Even if the temporal variation in simple reaction time had been absent from the first experiment, the duration of thermal strain was considered a potential influence on the effects of heat strain on performance. To assess the impact of this variable the duration of immersion was increased by fifty percent in the second experiment and performance was measured twice during immersion. This necessitated refinement of the water immersion technique to ensure that body temperature could be controlled over the extended immersion period.

In the first experiment, the test sessions were conducted in the morning only. To identify any effects of time of day on performance during thermal strain the immersions in the second experiment were conducted at two times of day.

CHAPTER 5

Experiment 2

Introduction

The principal aims of this experiment were firstly, to ascertain whether the effects of thermal strain observed in the previous experiment could be reproduced and, secondly, to examine the impact of heat strain on several additional psychological functions. To these ends, several of the tasks used in the previous study and a number of additional performance measures were selected for administration in the second experiment. As in the previous experiment, thermal strain was induced by warm water immersion to ensure that core temperature was maintained at a constant value during performance measurement.

An additional aim of the experiment was to examine the effects on performance of the duration of thermal strain. In the previous experiment, there was some evidence that the enhancement of reaction time in the variable foreperiod reaction task during heat strain was reduced towards the end of the test session. To assess the impact of the duration of thermal strain the duration of the immersion was extended by forty-five minutes (to two and a quarter hours) to allow the performance tasks to be administered on two occasions during immersion. Refinement of the water immersion technique was necessary to ensure that core temperature could be controlled over the extended immersion period.

In the previous experiment, the test sessions were conducted in the morning only. In the second experiment, the immersions were conducted at two times of day to investigate the impact of time of day on performance during thermal strain.

Selection of the Performance Measures

The tasks repeated from the first experiment were the semantic processing task, the verbal reasoning task, and the fixed and variable foreperiod simple reaction tasks. Significant reductions in reaction time during thermal strain had been observed in the first three tasks. Reaction time in the variable foreperiod reaction task had not differed significantly between the control and experimental immersions, but the task had revealed some evidence of temporal variation in performance during heat strain.

As the first experiment yielded no evidence that selective attention was affected by heat strain, the focused attention and categoric search tasks, and the Stroop task were excluded from the second study.

A dual-task measure of visual vigilance and compensatory tracking was substituted for the cognitive vigilance task used in the first experiment. Four further tasks were selected: an immediate recall task, a recognition memory task, a four-choice reaction task, and a tapping task. In light of evidence that thermal strain enhances the speed of motor responses (Goodman et al, 1984), this last measure was selected to assess the impact of heat strain on the speed of execution of motor actions.

Enhancing the Control of Core Temperature

The aim of the first experiment was to measure performance while core body temperature was maintained at a constant level of elevation. However, rectal temperature fell very slightly during performance testing in the experimental immersion. As the duration of the immersion was to be increased in the second experiment, it was necessary to control body temperature more precisely.

The slight decrease in core temperature observed during the experimental immersion in the first experiment may have occurred because a greater area of the skin surface was exposed to air than had been assumed during mathematical modelling of the physiological response to warm water immersion. It had been assumed that the body would be immersed to the neck, but a number of the participants adopted a posture in which the shoulders were held above the water surface. In addition, during performance testing, the forearms and hands were exposed to the air. It is possible, therefore, that heat loss from the body during the experimental immersion was greater than had been assumed during modelling.

Additional modelling using the Wissler model (Wissler, 1985) was conducted to identify the water temperature manipulations required to enhance the control of core temperature. The aim was to maintain rectal temperature at 38.3° C for a period of approximately one and a quarter hours to allow sufficient time for two performance testing sessions, separated by a brief rest period.

On the basis of the predictions derived from modelling, the participants in the second experiment were initially immersed in water at a temperature of 38.5° C, as in the previous study. When rectal temperature reached 38.15° C, approximately forty minutes after initial immersion, the water temperature was lowered to 37.45° C (rather than 37.40° C, as in the first experiment). Approximately fifteen minutes later, rectal temperature reached 38.3° C and the water temperature was raised to 37.6° C. Any deviations in core temperature from the value of 38.3° C after this point were counteracted by varying the water temperature by 0.1° C for each 0.1° C deviation in rectal temperature.

Method

Participants

The participants were sixteen male members of the staff of the Centre for Human Sciences, who volunteered to take part in the experiment. The participants ranged in age from twenty to thirty-six years, with a mean age of twenty-seven years. Before the study, each volunteer underwent a medical examination and gave informed, written consent to participate in the experiment.

Design

As in the previous experiment, a repeated-measures design was used in which each participant completed a control and experimental test session. In each session, the participant completed a battery of performance tests on three occasions: once in a thermoneutral environment prior to immersion to obtain baseline data and twice during immersion in water. In the control condition, the participant was immersed in water at a temperature of 35° C for a period of two and a quarter hours. In the experimental condition, the participant was immersed in water initially at a temperature of 38.5° C; the water temperature was subsequently manipulated as described above to maintain core temperature at 38.3° C while performance testing was conducted. One half of the sample completed their test sessions in the morning (with immersion from 1000 to 1215 h) and the remaining participants completed their sessions in the afternoon (immersion from 1515 to 1730 h). To identify any effects of the duration of the session on performance one half of the sample completed the performance tasks in a specific order and the remaining participants completed the tests in the reverse order. There was an interval of two days between each participant's sessions. The order of exposure to the control and experimental sessions was balanced across the participants.

Tests and Measures

Physiological Measures

As in the previous experiment, the physiological variables measured were rectal temperature, skin temperature at five sites (the back, chest, thigh, forehead and cheekbone), heart rate, and salivary cortisol level. The methods used to measure these variables are described in Chapter 4. Body temperatures and heart rate were recorded at intervals of thirty seconds. Saliva samples were collected on four occasions during each test session.

Psychological Performance Measures

Cognitive and psychomotor performance was measured using a battery of nine tasks. As in the previous experiment, the tasks were controlled by an IBM-compatible personal computer. As described in Chapter 4, the task stimuli were presented on a LCD computer projection panel, and responses were made using a waterproof console connected to the computer.

Four of the performance tasks were repeated from the first experiment: the fixed and variable foreperiod simple reaction tasks, the verbal reasoning task, and the semantic processing task (see Chapter 4). The remaining tasks are described below.

Immediate Recall

In this task, the participant was shown a list of twenty five-letter words (e.g. angel, horse). Each word was displayed individually for two seconds. The participant was instructed that, on completion of the list, he should write down the words that he could recall, in any order. Two minutes were allowed for recall of the words.

The immediate recall task was always presented as the first measure in the task battery. The task was linked with the recognition memory task described below.

Recognition Memory

Forty five-letter words were displayed individually on the screen, twenty of which had been presented in the immediate recall task. The participant was required to indicate as quickly as possible whether or not each word had been displayed in the recall task. The recognition task was always presented as the final measure in the task battery.

Dual-Task Performance: Tracking and Visual Vigilance

This task required the participant to perform a one-dimension, compensatory, velocity-control tracking task and simultaneously to monitor a visual display for signals. The tracking task target was displayed in the centre of the screen and the cursor moved horizontally. In the vigilance task, a series of single digits (1-9) was presented above the tracking display at a rate of one hundred per minute. The signal, a specific digit, was presented ten times per minute.

Before the task proper began, a few seconds were provided for practice of the tracking task and for the signal digit to be learnt. The duration of the task was three minutes.

Choice Reaction Time with Biased Probability of Stimulus Presentation

Smith (1985) described the use of biased probability choice reaction stimuli to assess attentional selectivity. In the present task, one of four letters ('A', 'B', 'C' or 'D') was presented in the centre of the screen. The participant was required to identify the letter as rapidly as possible by pressing one of four response buttons. One hundred and fifty trials were presented. The frequency of presentation of the letters was biased so that the letter 'B' was presented on forty percent of the trials, with each of the remaining letters presented on twenty percent of the trials. In addition, the order of presentation of the letters was controlled so that in half of the trials the stimulus was repeated from the previous trial.

Tapping

This task measured the rate at which a simple motor action was repetitively executed. The participant was instructed to tap repeatedly a response key as rapidly as possible for a period of one minute.

Subjective Measures

Mood

As in the previous experiment, mood was measured using the UMACL (Matthews et al 1990; see Chapter 4 for details).

Thermal Comfort

As in the previous study, subjective thermal comfort was measured using a nine point rating scale ranging from 'unbearably cold' (-4), through 'comfortable' (0), to 'unbearably hot' (4).

<u>Procedure</u>

The procedure followed in the test sessions was similar to that used in the previous experiment. A few days before his first test session, each participant completed a performance practice session in which the battery of tasks was completed three times.

The participants were requested to avoid alcohol for twenty-four hours prior to their test sessions. None of the participants smoked tobacco.

On the days of his test sessions, the participant reported at 0830 h (or 1345 h in the case of afternoon sessions) to a climate-controlled preparation room (maintained at 24° C T_{db}, with 40% rh). Following insertion of the rectal thermistor and instrumentation with the skin thermistors and ECG electrodes, the participant donned a tracksuit. At 0915 h (or 1430 h), physiological data recording was started, mood and thermal comfort measurements were taken, and a saliva sample was collected. The performance tasks were then administered to collect baseline data; the task battery took approximately thirty minutes to complete. One half of the sample completed the tasks in the following order: immediate recall, simple reaction time (fixed foreperiod), verbal reasoning, tracking with visual vigilance, choice reaction time, tapping, semantic processing, simple reaction time (variable foreperiod), and recognition memory. The remaining participants also completed the immediate recall and recognition tasks first and last, respectively, but the intervening tasks were completed in the reverse order.

At 1000 h (or 1515 h) the participant entered the Jacuzzi bath. The first performance measurement period was started at 1100 h (or 1615 h), one hour after initial immersion. On completion of this first performance assessment, the participant rested for fifteen minutes, still immersed. The battery of tasks was then administered for the second time during immersion, starting at 1145 h (or 1700h).

Mood and thermal comfort measurements were taken and saliva samples were collected on three occasions during immersion: immediately before the first performance assessment, during the fifteen-minute rest period, and on completion of the second performance assessment.

The participants were permitted to drink water *ad libitum* throughout their test sessions.

Results

Physiological Data

Body Temperatures and Heart Rate

The analysis of the body temperature and heart rate data focused on the three periods in each test session during which psychological performance was measured. In addition, the data recorded during the ten-minute period immediately prior to immersion were analysed to identify any differences between the conditions in the participants' physiological state before they entered the water.

The body temperature and heart rate data were analysed using repeated-measures analysis of variance. The independent variables included in the analysis were the condition, the time of day at which the test sessions were completed, and the measurement period (i.e. baseline, pre-immersion, first or second immersed performance assessment). Significant effects were analysed further using the Newman-Keuls range test and Bonferroni *t* test.

The Thermal Physiological Response to the Experimental Immersion

In both of the immersed performance measurement periods, rectal temperature was higher in the experimental than the control condition ($p < 0.001$ for both comparisons; see Table 5.1). Similarly, skin temperatures were higher ($p < 0.01$ for both comparisons at all skin sites; see Tables 5.2 and 5.3) and heart rate was elevated ($p < 0.001$ for both comparisons; see Table 5.4) in the experimental immersion.

In the morning immersion, rectal temperature was slightly but significantly higher in the first than in the second performance measurement period (means were 38.38 and 38.26° C, respectively; $p < 0.05$).

The mean rectal temperatures recorded during performance measurement varied slightly from the value of 38.30° C that had been sought (see Table 5.1). The values observed were similar to the mean value of 38.24° C recorded in the experimental immersion in the previous experiment.

As in the previous study, there was evidence of slight but significant temporal variation in core temperature during performance measurement in the experimental immersion. During the first performance measurement period, rectal temperature declined at a mean rate of -0.0024° C per minute ($p < 0.001$); the mean change in temperature over the course of the period was approximately -0.06° C. During the second performance measurement period, the mean rate of change in rectal temperature was -0.0003° C per minute ($p < 0.001$), with a mean change in temperature of approximately -0.01° C overall.

The Thermal Physiological Response to the Control Immersion

In the morning control test session, there were no significant differences in mean rectal temperature across the baseline period and the immersed performance measurement periods. In the afternoon session, rectal temperature was lower during each of the immersed performance measurement periods than during the baseline period ($p < 0.001$ for both comparisons). This reduction in core temperature from baseline to immersion was relatively small (0.22° C; see Table 5.1) and scrutiny of the thermal comfort ratings yielded no evidence of an associated change in subjective comfort (see Table 5.7).

As in the previous experiment, back, chest, and thigh skin temperatures were higher during the control immersion than in the baseline period ($p < 0.001$ for all comparisons; see Table 5.2), reflecting the impact of the water temperature of 35° C. Cheek and forehead skin temperatures also increased during immersion, but this variation was not significant (see Table 5.3).

There were no significant differences in heart rate across the baseline period and the immersed performance measurement periods (see Table 5.4).

The Baseline and Pre-immersion Periods

There were no significant differences between the control and experimental sessions in body temperatures or heart rate during either the baseline or pre-immersion periods.

The mean rectal temperatures recorded during the baseline and pre-immersion periods were significantly higher in the afternoon than the morning ($p < 0.001$ for both comparisons; see Table 5.1), reflecting the diurnal rhythm in core temperature.

	Control Session		Experimental Session	
	a.m.	p.m.	a.m.	p.m.
Baseline	36.80 (0.27)	37.20 (0.34)	36.80 (0.23)	37.19 (0.22)
Pre-immersion	36.77 (0.26)	37.16 (0.31)	36.73 (0.19)	37.13 (0.18)
First Performance Session	36.75 (0.18)	37.00 (0.25)	38.38 (0.03)	38.27 (0.11)
Second Performance Session	36.76 (0.15)	36.98 (0.26)	38.26 (0.09)	38.24 (0.10)

Table 5.1. Mean rectal temperatures (° C) during baseline and immersed performance testing, and in the pre-immersion period. Standard deviations are shown in parentheses

	Control Session		Experimental Session	
	a.m.	p.m.	a.m.	p.m.
Back Skin Temperature				
Baseline	34.25 (0.62)	34.36 (0.54)	33.80 (0.97)	33.72 (1.22)
Pre-immersion	34.04 (0.92)	34.11 (0.50)	33.35 (1.17)	33.58 (1.09)
First Performance Session	35.45 (0.44)	35.61 (0.22)	37.90 (0.83)	37.90 (0.12)
Second Performance Session	35.49 (0.13)	35.57 (0.25)	37.95 (0.11)	37.85 (0.41)
Chest Skin Temperature				
Baseline	33.95 (0.77)	35.15 (0.71)	33.99 (1.06)	34.40 (1.21)
Pre-immersion	34.00 (0.85)	35.32 (0.54)	34.21 (1.13)	34.52 (1.14)
First Performance Session	35.44 (0.07)	35.70 (0.24)	38.01 (0.05)	37.93 (0.10)
Second Performance Session	35.50 (0.20)	35.72 (0.28)	38.06 (0.04)	38.03 (0.14)
Thigh Skin Temperature				
Baseline	33.22 (0.75)	32.19 (0.99)	32.89 (0.47)	31.53 (0.84)
Pre-immersion	33.11 (0.81)	32.08 (0.95)	32.39 (0.60)	31.65 (0.70)
First Performance Session	35.43 (0.63)	35.64 (0.20)	37.88 (0.51)	37.89 (0.09)
Second Performance Session	35.49 (0.17)	35.56 (0.21)	37.98 (0.12)	37.92 (0.12)

Table 5.2. Mean body skin temperatures (° C) during baseline and immersed performance testing, and in the pre-immersion period. Standard deviations are shown in parentheses

	Control Session		Experimental Session	
	a.m.	p.m.	a.m.	p.m.
Cheek Skin Temperature				
Baseline	34.81 (0.42)	35.84 (0.49)	34.77 (0.38)	34.96 (0.42)
Pre-immersion	34.49 (0.42)	35.66 (0.55)	34.55 (0.44)	34.78 (0.42)
First Performance Session	34.75 (0.20)	36.35 (0.02)	36.81 (0.09)	36.89 (0.39)
Second Performance Session	34.90 (0.16)	36.00 (0.37)	36.55 (0.06)	36.97 (0.69)
Forehead Skin Temperature				
Baseline	34.57 (0.30)	34.36 (0.80)	34.15 (0.42)	34.92 (0.42)
Pre-immersion	34.30 (0.33)	34.29 (0.43)	34.14 (0.31)	33.78 (0.35)
First Performance Session	34.65 (0.29)	34.19 (0.18)	36.61 (0.45)	36.87 (0.78)
Second Performance Session	34.58 (0.49)	34.68 (0.11)	36.41 (0.80)	36.79 (0.56)

Table 5.3. Mean face skin temperatures (° C) during baseline and immersed performance testing, and in the pre-immersion period. Standard deviations are shown in parentheses

	Control Session		Experimental Session	
	a.m.	p.m.	a.m.	p.m.
Baseline	67 (14)	82 (14)	69 (4)	73 (12)
Pre-immersion	69 (10)	79 (13)	70 (7)	75 (12)
First Performance Session	68 (8)	75 (13)	93 (7)	103 (13)
Second Performance Session	68 (9)	77 (17)	92 (6)	104 (12)

Table 5.4. Mean heart rate (beats per minute) during baseline and immersed performance testing, and in the pre-immersion period. Standard deviations are shown in parentheses

Salivary Cortisol

The salivary cortisol data were analysed using repeated-measures analysis of covariance, with the baseline value treated as a covariate. The data were transformed to meet the assumptions of parametric testing. The independent variables included in the analysis were the condition, the time at which the saliva samples were collected, the time of day at which the test sessions were conducted, and the order of exposure to the two conditions. Mean cortisol values are shown in Table 5.5; the means have been adjusted on the basis of baseline values, and back-transformed and adjusted for bias.

Cortisol level was not significantly affected by the independent variables. Cortisol concentration tended to be higher in the morning immersions and during thermal strain.

	Control Immersion		Experimental Immersion	
	a.m.	p.m.	a.m.	p.m.
Before First Immersed Performance Session	1.6 (0.6)	1.2 (0.3)	3.1 (6.8)	1.8 (0.5)
Between Immersed Performance Sessions	1.9 (1.0)	1.3 (0.5)	2.9 (5.3)	1.8 (0.5)
After Second Immersed Performance Session	1.8 (1.0)	1.1 (0.3)	2.2 (2.6)	2.4 (0.8)
Mean	1.8 (0.9)	1.2 (0.4)	2.7 (4.9)	2.0 (0.6)

Table 5.5. Mean salivary cortisol concentration (nmol/L). Standard deviations are shown in parentheses

Subjective Data

Mood

Scores on the Energetic Arousal, Tense Arousal, Hedonic Tone, and Anger/Frustration scales of the UMACL were analysed using repeated-measures analysis of covariance, with baseline values treated as covariates. The independent variables included in the analysis were the condition, the time at which mood was measured, the time of day at which the test sessions were conducted, and the order of exposure to the two conditions. Where necessary, the mood data were transformed to meet the assumptions of parametric testing. The means reported below have been adjusted on the basis of baseline values, and where applicable, have been back-transformed and corrected for bias.

Tense Arousal was higher in the experimental than the control immersion ($F = 12.11$, $df = 1, 10$, $p < 0.01$; see Table 5.6). Hedonic Tone was lower during the experimental immersion ($F = 20.51$, $df = 1, 10$, $p < 0.01$; see Table 5.6). Neither of these effects varied with the duration of the experimental immersion.

Hedonic Tone was affected by the time of day at which the immersions were conducted ($F = 16.14$, $df = 1, 10$, $p < 0.01$); mean scores were lower in the morning than in the afternoon (see Table 5.6).

Energetic Arousal and Anger/Frustration were unaffected by the independent variables. Energetic Arousal tended to be lower and Anger/Frustration tended to be higher during thermal strain (see Table 5.6).

Thermal Comfort

The mean ratings of thermal comfort in the control and experimental sessions are shown in Table 5.7. These indicate that the participants were uncomfortably warm during the experimental immersion.

The Effects of Warm Water Immersion on Thermal Physiological and Psychological State: Summary

The participants experienced marked thermal strain during the experimental immersion, as evidenced by the significant elevation of rectal and skin temperatures, and heart rate. This heat strain was accompanied by an increase in subjective discomfort. The mean values of body temperatures and heart rate were comparable with those observed in the previous experiment. As in the previous study, there was evidence of very slight temporal variation in core temperature during performance testing in the experimental immersion.

Cortisol secretion tended to be higher during thermal strain. The pattern of variation in mood with heat strain was similar to that observed in the previous experiment. Thermal strain increased Tense Arousal and reduced ratings of Hedonic Tone.

Energetic Arousal tended to be lower and Anger/Frustration tended to be higher in the experimental immersion.

	Control Immersion		Experimental Immersion	
	a.m.	p.m.	a.m.	p.m.
Energetic Arousal				
Before First Immersed Performance Session	23.1 (3.8)	24.3 (2.5)	19.5 (4.1)	23.5 (4.3)
Between Immersed Performance Sessions	21.6 (3.8)	23.3 (2.5)	20.2 (3.4)	22.4 (3.7)
After Second Immersed Performance Session	22.0 (4.2)	23.6 (2.1)	19.2 (3.8)	22.9 (4.4)
Mean	22.2 (3.9)	23.7 (2.2)	19.6 (3.8)	22.9 (4.1)
Tense Arousal				
Before First Immersed Performance Session	10.9 (2.1)	13.1 (3.2)	13.1 (3.8)	11.5 (2.4)
Between Immersed Performance Sessions	10.9 (3.8)	10.9 (1.7)	13.1 (4.4)	13.1 (5.0)
After Second Immersed Performance Session	11.5 (2.9)	11.5 (2.4)	14.0 (4.5)	15.2 (7.5)
Mean	11.1 (2.9)	11.8 (2.4)	13.4 (4.2)	13.3 (5.0)

continued

Table 5.6. Mean mood scores. Standard deviations are shown in parentheses

	Control Immersion		Experimental Immersion	
	a.m.	p.m.	a.m.	p.m.
Hedonic Tone				
Before First Immersed Performance Session	29.5 (3.0)	29.5 (1.6)	28.7 (3.1)	29.7 (3.0)
Between Immersed Performance Sessions	29.1 (3.5)	29.9 (2.4)	26.5 (3.7)	29.4 (3.1)
After Second Immersed Performance Session	29.1 (2.8)	29.6 (2.3)	27.1 (4.7)	29.5 (4.1)
Mean	29.2 (3.1)	29.7 (2.1)	27.4 (3.8)	29.5 (3.4)
Anger/Frustration				
Before First Immersed Performance Session	5.1 (0.0)	5.1 (0.3)	5.7 (2.0)	5.4 (0.6)
Between Immersed Performance Sessions	5.1 (0.6)	5.1 (0.3)	6.0 (2.7)	5.7 (2.0)
After Second Immersed Performance Session	5.4 (1.0)	5.4 (1.3)	6.4 (3.6)	5.7 (1.4)
Mean	5.2 (0.5)	5.2 (0.6)	6.0 (2.8)	5.6 (1.3)

Table 5.6. (continued). Mean mood scores. Standard deviations are shown in parentheses

	Control Session		Experimental Session	
	a.m.	p.m.	a.m.	p.m.
Baseline	0.1 (0.4)	-0.3 (0.5)	0.1 (0.4)	-0.3 (0.5)
Before First Immersed Performance Session	-0.1 (0.4)	0.1 (0.8)	1.8 (0.7)	1.5 (0.6)
Between Immersed Performance Sessions	0 (0)	0.2 (0.7)	1.7 (0.8)	1.5 (0.8)
After Second Immersed Performance Session	0 (0)	0.2 (0.7)	1.7 (0.8)	1.6 (0.7)

Table 5.7. Mean thermal comfort ratings (a rating of 0 indicates comfort). Standard deviations are shown in parentheses

Psychological Performance Data

The performance data were analysed using repeated-measures analysis of covariance, with baseline performance treated as a covariate. The independent variables included in the analysis were the condition, the duration of immersion, the time of day at which the immersions were conducted, the order in which the performance tasks were completed, and the order of exposure to the two conditions. In addition, task variables were included, as appropriate. Where necessary, the performance data were transformed to meet the assumptions of parametric testing. Significant effects were analysed further using the Newman-Keuls range test and Bonferroni *t* test.

As a result of an error in the software used to control the performance measures complete data sets for the semantic processing task were obtained for just nine participants. Consequently, these data were not subjected to inferential statistical analysis.

As in the previous study, only those results that are pertinent to the focus of the experiment are described. Performance was affected by several of the independent variables, but only the main effects of thermal strain and the interactions of thermal strain with other variables are detailed. The means reported have been adjusted on the basis of baseline performance and, where applicable, the means have been back-transformed and adjusted for bias. The mean values of the performance variables are shown in Appendix II.

The Effects of Thermal Strain on Performance

The generalized increase in performance speed during thermal strain observed in the previous experiment was replicated in this study. Faster performance during thermal strain was evident in several of the tasks. Shorter reaction times during heat strain were observed in the choice reaction task ($F = 15.32$, $df = 1, 7$, $p < 0.01$; see Figure 5.1) and in both simple reaction tasks: the variable foreperiod task ($F = 115.37$, $df = 1, 7$, $p < 0.001$; see Figure 5.2) and the fixed foreperiod task ($F = 9.96$, $df = 1, 7$, $p < 0.05$; see Figure 5.3). In the visual vigilance task, reaction time to signals was lower in the experimental immersion ($F = 14.82$, $df = 1, 7$, $p < 0.01$; see Figure 5.4). The magnitude of the decrease in reaction time in these tasks ranged from four to nine percent. In the verbal reasoning task, the number of trials completed was greater during thermal strain ($F = 6.68$, $df = 1, 6$, $p < 0.05$; see Figure 5.5). In the tapping task, tapping rate was higher in the experimental immersion ($F = 35.74$, $df = 1, 7$, $p < 0.001$; see Figure 5.6).

No significant effects of thermal strain on reaction time were observed in the verbal reasoning and recognition memory tasks. However, mean reaction times in these tasks tended to be shorter during heat strain (see Table 5.8).

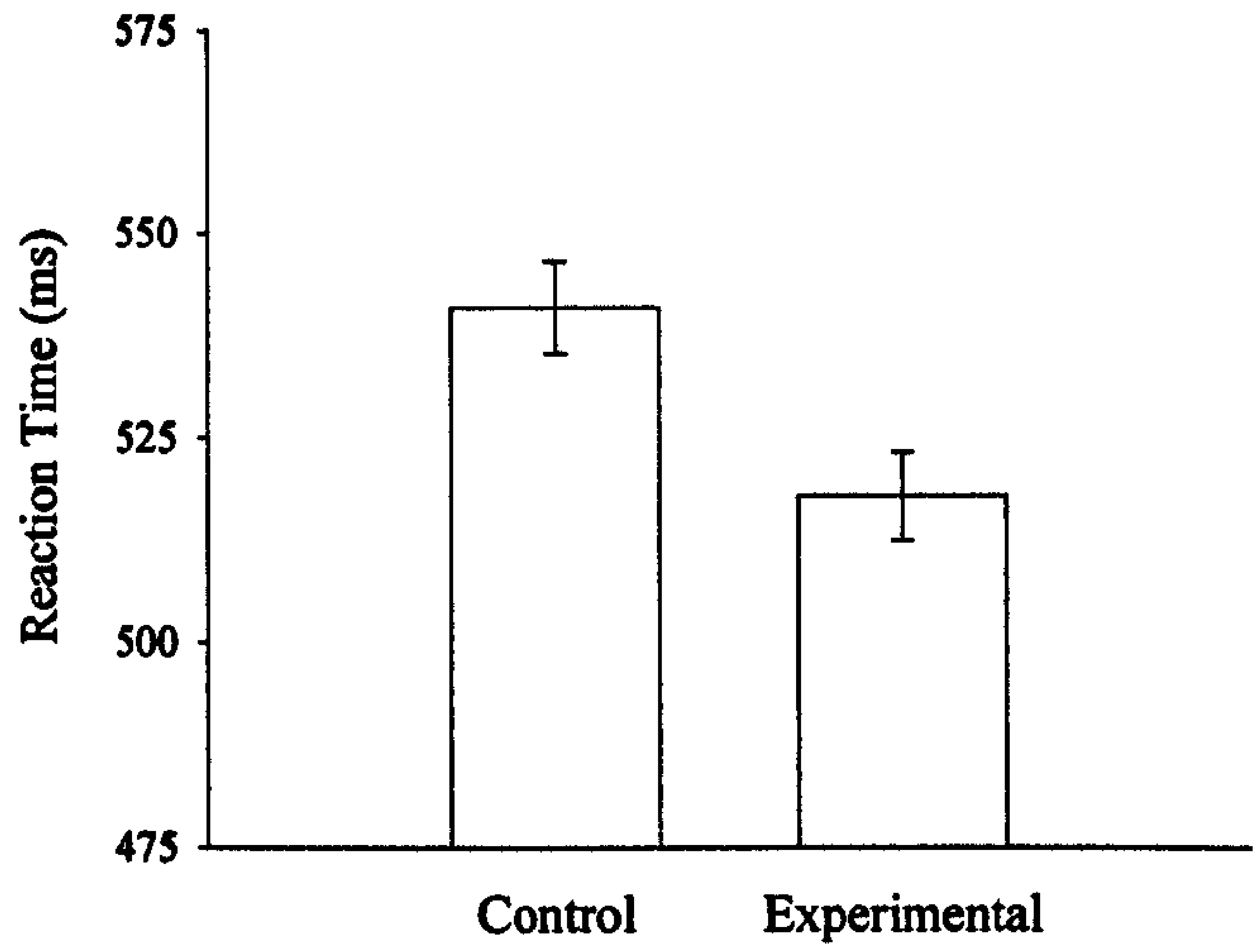

Figure 5.1. Choice reaction task: Mean reaction time in the control and experimental immersions. Standard errors of the mean are shown (95% confidence intervals)

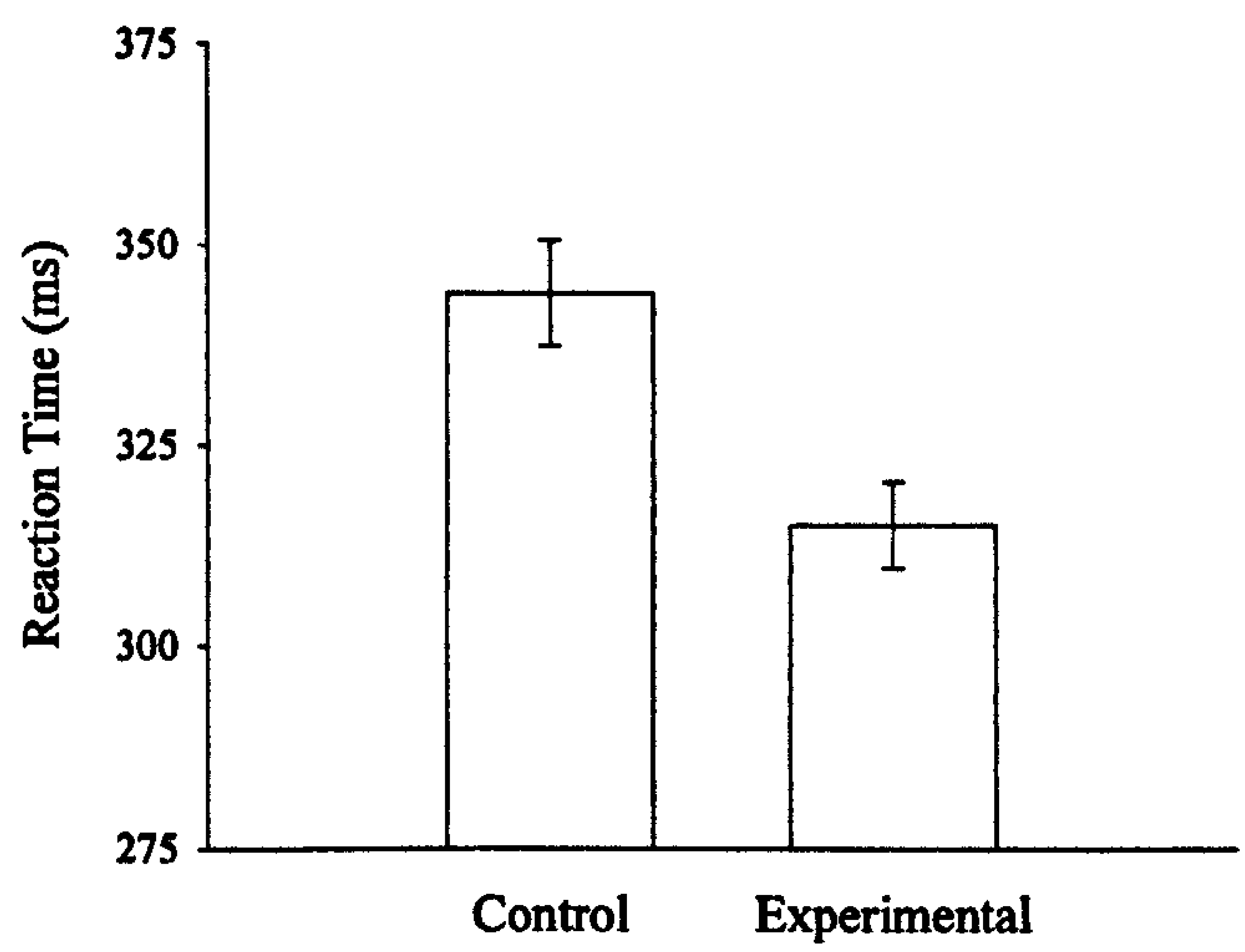

Figure 5.2. Variable foreperiod simple reaction task: Mean reaction time in the control and experimental immersions. Standard errors of the mean are shown (95% confidence intervals)

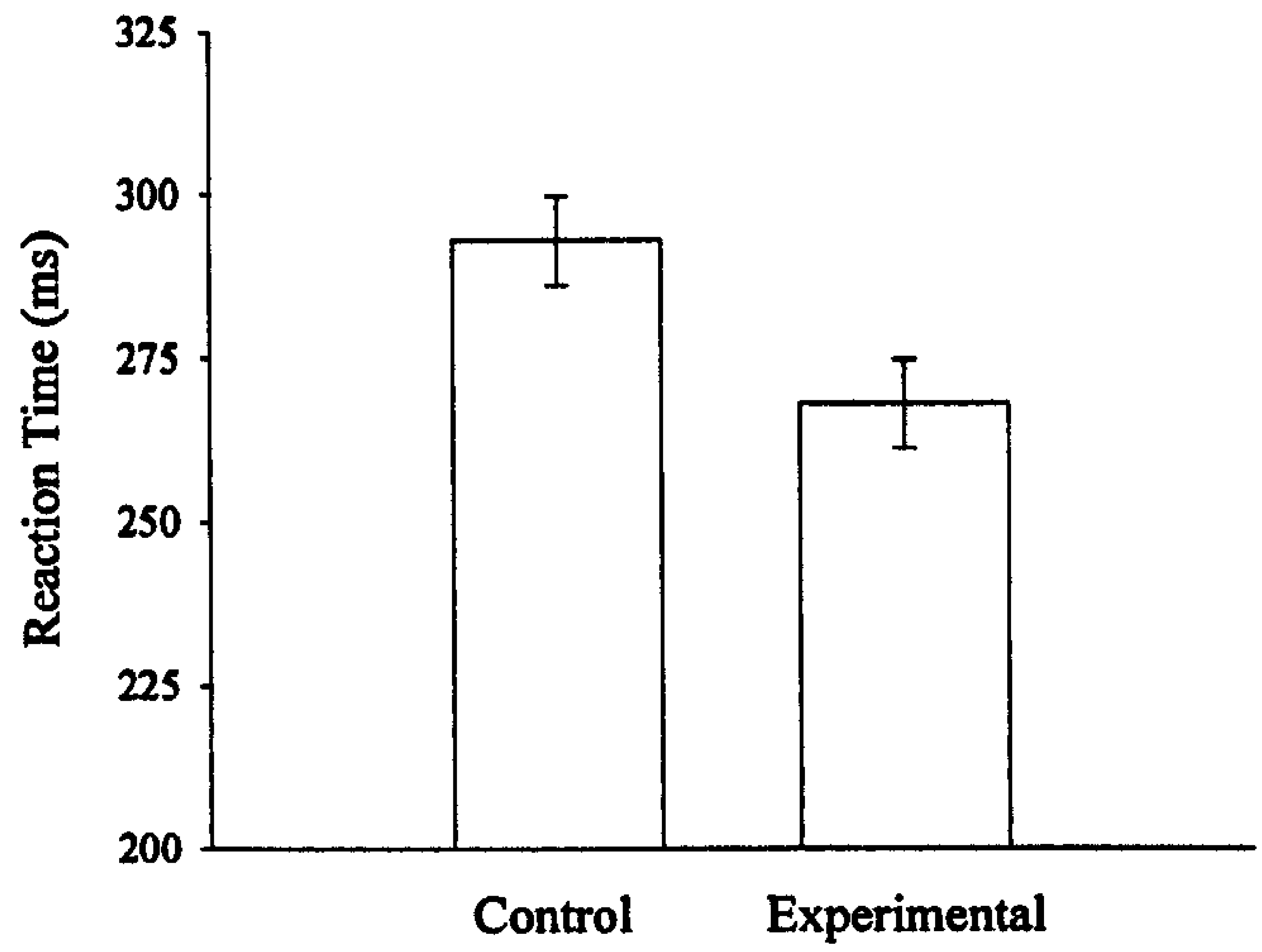

Figure 5.3. Fixed foreperiod simple reaction task: Mean reaction time in the control and experimental immersions. Standard errors of the mean are shown (95% confidence intervals)

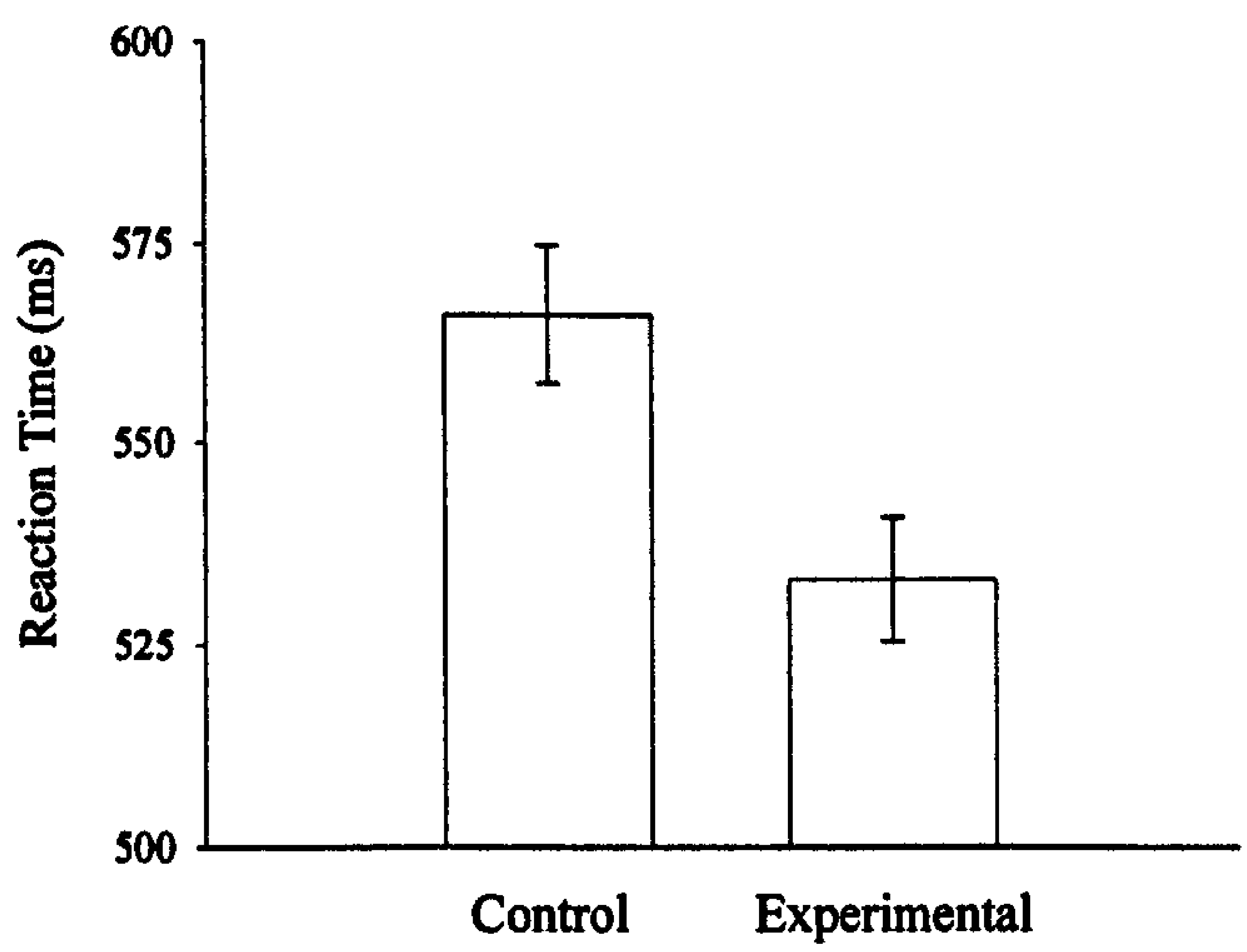

Figure 5.4. Vigilance task: Mean reaction time to signals in the control and experimental immersions. Standard errors of the mean are shown (95% confidence intervals)

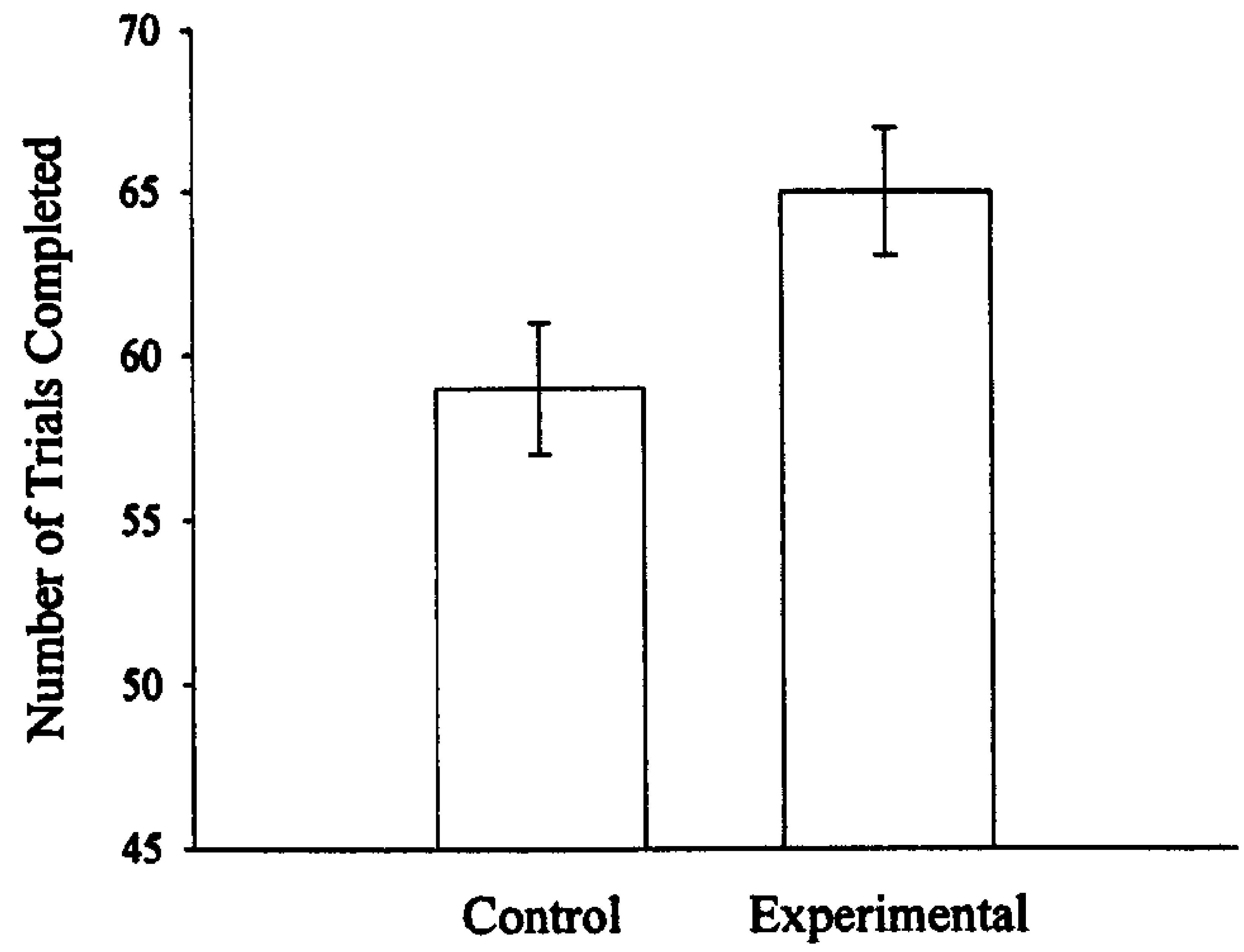

Figure 5.5. Verbal reasoning task: Mean number of trials completed in the control and experimental immersions. Standard errors of the mean are shown (95% confidence intervals)

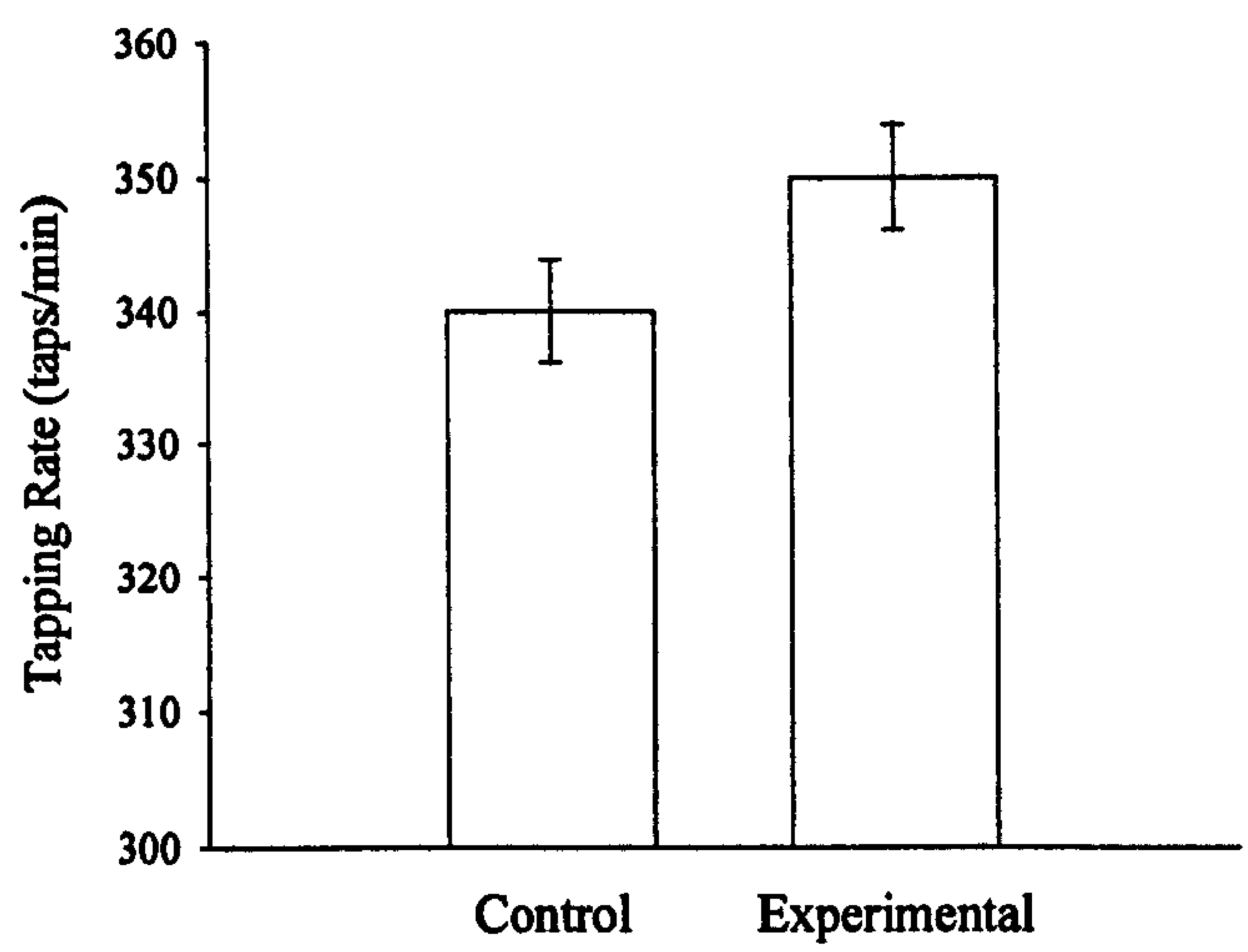

Figure 5.6. Tapping task: Mean tapping rate in the control and experimental immersions. Standard errors of the mean are shown (95% confidence intervals)

	Control Immersion	Experimental Immersion
Verbal Reasoning Task	3038 (762)	2780 (518)
Recognition Memory Task	951 (140)	848 (168)

Table 5.8. Mean reaction times (ms) in the verbal reasoning and recognition memory tasks. Standard deviations are shown in parentheses

Consistent with the results of the previous experiment, there was no evidence that the faster performance observed during thermal strain reflected a trade-off between the speed and accuracy of performance. Performance accuracy did not vary significantly with heat strain. Mean accuracy scores are shown in Table 5.9.

	Control Immersion	Experimental Immersion
Verbal Reasoning Task	85 (17)	83 (19)
Recognition Memory Task	67 (16)	67 (12)
Choice Reaction Task	99 (3)	99 (3)

Table 5.9. Mean accuracy scores (% correct) in the verbal reasoning, recognition memory, and choice reaction tasks. Standard deviations are shown in parentheses

The increase in signal detection rate during thermal strain observed in the previous experiment was not replicated in this study. Signal detection rate did not vary significantly between the control and experimental immersions (the mean detection rates were 9.6 and 9.7 signals per minute, respectively). The false detection rate did not differ between the control and experimental immersions (the mean rate was 0.3 false positives per minute in both immersions). The failure to reproduce the increase in signal detection rate observed in the previous study may stem from differences between the vigilance tasks used in the two experiments.

Performance on the compensatory tracking task, which was completed simultaneously with the vigilance task, was not affected by thermal strain. Root mean square error did not differ significantly between the control and experimental immersions (the mean values were 2670 and 2672, respectively). The number of edge violations did not vary significantly with heat strain (the mean values were 24 and 23 in the control and experimental immersions, respectively).

There were no main effects of thermal strain on performance in the immediate recall task. The number of words recalled was slightly higher during heat strain, but this difference was not significant (means were 7.7 and 8.6 words in the control and experimental immersions, respectively). The percentage of the words recalled that were correct did not vary significantly between the control and experimental immersions (means were 87% and 89%, respectively).

The Effects of the Duration of Thermal Strain on Performance

Psychological performance was largely unaffected by the duration of heat strain. Main effects of the duration of immersion were observed in a number of the tasks, but there was little evidence that the impact of immersion duration varied between the control and experimental conditions. No two-way interactions between the condition and the duration of immersion were observed. A number of three-way interactions involving the condition and the duration of immersion are described below, but given the relatively small sample used in this experiment, it is probable that these effects are not robust.

In the variable foreperiod simple reaction task, reaction time was affected by an interaction of the condition, the duration of the immersion, and the order in which the performance tasks were completed ($F = 12.22$, $df = 1, 8$, $p < 0.01$; means are shown in Table 5.10). Analysis of this effect indicated that when the tasks were completed in the 'standard' order (in which the variable foreperiod task was the penultimate measure), reaction time in the first immersed performance measurement period was lower in the experimental than in the control condition ($p < 0.05$). When the tasks were completed in the 'reverse' order (in which the variable foreperiod task was the second measure), reaction time in the second performance measurement period was shorter in the experimental than in the control condition ($p < 0.01$).

	Control Immersion		Experimental Immersion	
	Standard Task Order	Reverse Task Order	Standard Task Order	Reverse Task Order
First Performance Session	351 (35)	327 (41)	313 (41)	313 (37)
Second Performance Session	349 (45)	349 (42)	328 (28)	304 (37)

Table 5.10. Variable foreperiod simple reaction task: Mean reaction times (ms) for condition, duration of immersion, and task order. Standard deviations are shown in parentheses

Reaction time in the variable foreperiod reaction task was also affected by an interaction of the condition, the duration of the immersion, and the time of day at which the immersions were conducted ($F = 15.28$, $df = 1, 8$, $p < 0.01$; means are shown in Table 5.11). Compared with the control immersion, heat strain enhanced reaction time in the first performance measurement period in the mornings ($p < 0.05$) and in the second measurement period in the afternoons ($p < 0.01$).

	Control Immersion		Experimental Immersion	
	a.m.	p.m.	a.m.	p.m.
First Performance Session	353 (36)	326 (40)	314 (33)	312 (45)
Second Performance Session	349 (53)	349 (35)	331 (35)	301 (30)

Table 5.11. Variable foreperiod simple reaction task: Mean reaction times (ms) for condition, duration of immersion, and time of day. Standard deviations are shown in parentheses

In the immediate recall task, the number of words recalled was affected by an interaction of the condition, the duration of the immersion, and the time of day at which the immersions were conducted ($F = 15.68$, $df = 1, 8$, $p < 0.01$). However, further analysis of this interaction revealed no significant differences across the means.

In the tapping task, tapping rate was affected by an interaction of the condition, the duration of immersion, and the order of exposure to the two conditions (F 7.23, $df = 1, 8$, $p < 0.05$). Further analysis indicated that this interaction reflected variation in the effect of the duration of immersion between the participants' first and second test sessions, irrespective of the condition.

The Effects of Time of Day on Performance during Thermal Strain

Main effects of the time of day at which the immersions were conducted were observed in a number of the tasks, but there was little evidence that the effects of time of day varied with thermal strain. No two-way interactions between the condition and the time of day were evident. A number of three-way interactions involving the condition and the time of day were observed, but, again, it is probable that these effects are not robust.

In the choice reaction task, accuracy was affected by an interaction of the condition, the time of day, and the order in which the performance tasks were completed ($F = 5.59$, $df = 1, 7$, $p < 0.05$; means are shown in Table 5.12). Analysis of this effect indicated that when the tasks were completed in the 'standard' order (in which the choice reaction task was the fifth measure) accuracy in the afternoon session was poorer in the experimental than the control immersion ($p < 0.05$).

	Control Immersion		Experimental Immersion	
	a.m.	p.m.	a.m.	p.m.
Standard Task Order	99.0 (2.7)	99.4 (3.3)	99.3 (2.4)	98.8 (3.8)
Reverse Task Order	99.4 (2.1)	99.1 (1.7)	99.1 (2.1)	99.1 (2.0)

Table 5.12. Choice reaction task: Mean accuracy scores (% correct) for condition, time of day, and task order. Standard deviations are shown in parentheses

As noted above, reaction time in the variable foreperiod simple reaction task was affected by an interaction of the condition, the time of day, and the duration of immersion ($F = 15.28$, $df = 1, 8$, $p < 0.01$; see Table 5.11). Compared with the control immersion, reaction time was lower during thermal strain in the first performance measurement period in the mornings ($p < 0.05$) and in the second measurement period in the afternoons ($p < 0.01$).

Reaction time in the variable foreperiod reaction task was also affected by an interaction of the condition, the time of day, and the order of exposure to the conditions. Further analysis indicated that this interaction reflected variation in the effect of time of day between the participants' first and second test sessions, irrespective of the condition.

As noted above, the number of words recalled in the immediate recall task was affected by an interaction of the condition, the time of day at which the immersions were conducted, and the duration of the immersion ($F = 15.68$, $df = 1, 8$, $p < 0.01$). However, further analysis of this interaction revealed no significant variation across the means.

The Effects of Task Variables on Performance during Thermal Strain

In the verbal reasoning task, reaction time was affected by an interaction between the condition and the syntactic complexity of the stimuli ($F = 3.10$, $df = 3, 20$, $p < 0.05$; means are shown in Table 5.13). This effect was also observed in the previous experiment, but the precise pattern of variation differed between the two studies. Comparison of the reaction times to each of the syntactic categories of stimuli in the control and experimental immersions indicated that reaction time to the negative, passive statements was shorter during thermal strain ($p < 0.01$). Reaction time to the remaining categories did not vary significantly with heat strain. In both the control and experimental immersions, reaction time to the positive, active statements was shorter than those to the other syntactic categories ($p < 0.001$ for all comparisons). Reaction time to the negative, active statements was shorter than those to the negative, passive statements ($p < 0.001$ in both immersions) and the positive, passive statements ($p < 0.01$ in both immersions). In the control immersion, reaction time to the positive, passive statements was less than that to the negative, passive statements ($p < 0.01$). During thermal strain, reaction time to the positive, passive and the negative, passive statements did not differ significantly.

	Control Immersion	Experimental Immersion
Positive, active voice	2517 (580)	2325 (449)
Positive, passive voice	3229 (964)	3023 (668)
Negative, active voice	2898 (622)	2664 (447)
Negative, passive voice	3604 (957)	3149 (560)

Table 5.13. Verbal reasoning task: Mean reaction times (ms) for condition and syntactic category of stimuli. Standard deviations are shown in parentheses

The Effects of Time on Task on Performance during Thermal Strain

The data for each one-minute block of the simple reaction and vigilance tasks were analysed to explore the impact of time on task on performance. Performance on the variable foreperiod reaction task was unaffected by time on task. In the vigilance task, time on task affected reaction time to signals ($F = 7.50$, $df = 2, 15$, $p < 0.01$), but this effect did not vary with heat strain.

Reaction time in the fixed foreperiod simple reaction task was affected by an interaction between the condition and time on task ($F = 4.25$, $df = 2, 15$, $p < 0.05$; means are shown in Table 5.14). Analysis of this effect indicated that reaction time was shorter during the experimental than the control immersion in the first minute ($p < 0.05$) and in the final minute of the task ($p < 0.01$).

	Control Immersion	Experimental Immersion
First Minute	290 (57)	267 (37)
Second Minute	287 (44)	275 (34)
Third Minute	298 (51)	260 (33)

Table 5.14. Fixed foreperiod simple reaction task: Mean reaction times (ms) for condition and minute of the task. Standard deviations are shown in parentheses

Performance on the Semantic Processing Task

As complete data sets for the semantic processing task were obtained for just nine participants, this task was not subjected to inferential statistical analysis. Descriptive statistics for the task are shown in Table 5.15. Scrutiny of the means suggested that performance was faster during thermal strain. Accuracy did not vary markedly between the control and the experimental immersions. These results are consistent with the effects of heat strain on performance of the task observed in the previous experiment.

	Control Session		Experimental Session	
	a.m.	p.m.	a.m.	p.m.
Reaction Time (ms)				
Baseline	1566 (395) [7]	1311 (252) [7]	1491 (491) [6]	1401 (291) [8]
First Performance Session	1453 (396) [8]	1311 (206) [7]	1425 (352) [7]	1272 (269) [8]
Second Performance Session	1404 (380) [8]	1267 (237) [7]	1340 (295) [8]	1214 (276) [6]
Number of Trials Completed				
Baseline	111 (31)	128 (25)	117 (33)	120 (26)
First Performance Session	119 (32)	125 (19)	122 (32)	135 (28)
Second Performance Session	124 (33)	131 (24)	127 (28)	141 (32)
Accuracy (percent correct)				
Baseline	97 (2)	94 (4)	97 (2)	93 (5)
First Performance Session	95 (2)	94 (4)	95 (2)	93 (3)
Second Performance Session	96 (3)	92 (6)	94 (3)	90 (6)

Table 5.15. Semantic processing task: Performance means. Standard deviations are shown in parentheses. Values of n are shown in brackets

Discussion

The principal aims of this experiment were to assess the extent to which the performance changes observed in the previous experiment could be replicated and to measure the impact of thermal strain on several additional mental functions. The experiment also sought to investigate the effects of the duration of thermal strain on performance. In addition, the effects of time of day on performance during heat strain were examined.

The participants experienced marked thermal strain during the experimental immersion, as evidenced by the significant elevation of core and skin temperatures, and heart rate. The values of these variables were comparable with those observed in the experimental immersion in the first experiment. In spite of an attempt to improve the control of core body temperature, slight but significant temporal variation in core temperature during performance measurement was also evident in this experiment. In addition, mean rectal temperature in the morning experimental immersion was higher in the first than in the second performance measurement period, but the difference between these two values was small (0.12° C).

The pattern of mood change during thermal strain was similar to that observed in the first experiment. Tense Arousal increased and ratings of Hedonic Tone were reduced. In addition, Energetic Arousal tended to decrease and Anger/Frustration tended to increase during heat strain. Cortisol secretion tended to be elevated during the experimental immersion.

The principal effect of thermal strain observed in the first experiment was a generalized decrease in reaction time, without variation in accuracy. This finding was replicated in the present experiment. Reaction times in the simple and four-choice reaction tasks, and reaction time to signals in the vigilance task were significantly lower during heat strain. Reaction times in the recognition memory and verbal reasoning tasks tended to be shorter in the experimental immersion, but this variation was not significant. Enhanced speed of performance was also evident in a significant increase in the number of trials completed in the verbal reasoning task. In addition, the rate of tapping was significantly higher during thermal strain. As in the previous experiment, there was no evidence of a trade-off between the speed and accuracy of performance during thermal strain. Performance accuracy did not vary significantly with heat strain in any of the tasks.

In Chapter 4, it was suggested that the pattern of faster performance without variation in accuracy observed during thermal strain may be due, at least in part, to an enhancement of nerve conduction velocity and the speed of motor responses associated with raised body temperature. A number of investigators have observed a positive relationship between body temperature and sensory nerve conduction velocity (Buchtal and Rosenfalk, 1966; Stegeman and De Weerd, 1982; Trojaborg et al, 1992). As noted previously, it seems reasonable to assume that that this temperature-related increase in conduction velocity applies as much to motor nerves as to sensory nerves. Goodman et al (1984) presented evidence that elevation of limb temperature enhances the speed of execution of motor responses. However, their data were collected from just two volunteers. The increase in the rate of tapping (which is predominantly a measure of motor output) observed in the present experiment is consistent with Goodman and his colleagues' conclusion that elevation of temperature increases the speed of motor responding.

The improvement in signal detection rate observed in the first experiment was not replicated in this study. The failure to reproduce the effect may have its origin in differences between the vigilance tasks used in the two experiments. The event rate was the same in both tasks, but the signal rate was lower in the task used in the first experiment (eight compared with ten signals per minute). More significantly, the vigilance task used in the first experiment required the detection of repetitions of three-digit numbers, placing a significant load on working memory. In contrast, the demand imposed by the vigilance task used in the present experiment was substantially less (the task required the detection of a single, specific digit). This is evidenced by the higher signal detection rate and lower false alarm rate in the control immersion in the present experiment, in spite of the vigilance task being administered in conjunction with a tracking task. The absence of variation in vigilance performance between the control and experimental immersions may reflect a ceiling effect due to the relative ease of the task.

Tracking performance did not vary significantly with thermal strain and no trends in the data were discernible. Previous research has been almost entirely consistent in indicating that exposure to heat stress impairs tracking. The absence of any effects of heat strain on tracking in this experiment is not readily explicable, particularly in light of the fact that the task was sensitive to variation in performance with time of day (significantly fewer edge violations were observed in the afternoon immersions). There is some evidence in the literature that task variables, in particular, task demand, affect the impact of heat stress on tracking performance. It is conceivable that task characteristics underlie the absence of variation in tracking performance between the control and experimental immersions in the present experiment, but as task variables were not explicitly manipulated, the possible impact of these cannot be ascertained.

Performance in the immediate recall task did not vary significantly with thermal strain. With the exception of a non-significant decrease in reaction latency, recognition memory was also unaffected by heat strain. It is quite probable that these tasks were insufficiently sensitive to detect any variation in performance in a sample of just sixteen individuals (indeed, these measures were excluded from the first experiment on this basis; see Chapter 3). There is a dearth of data in the thermal stress literature on the effects of heat on memory. Holland et al (1985) found that thermal strain did not affect either memory for prose or digit span. O'Connor (1994) reported that heat strain enhanced reaction time without affecting accuracy in a memory search task. The nature of the memory search strategy employed by the participants did not vary between the control and experimental conditions.

An important objective of this experiment was to examine the impact of the duration of thermal strain on performance. The period during which core temperature was maintained at an elevated value was approximately forty-five minutes longer than that in the first experiment. However, the duration of heat strain had little impact on performance. No two-way interactions between the condition and the duration of immersion were evident. In the variable foreperiod simple reaction task, reaction time was affected by an interaction between the duration of thermal strain and the order in which the performance tasks were completed. Analysis of this interaction yielded an unremarkable pattern of results. Reaction time in this task was also affected by an interaction between the duration of thermal strain and the time of day. Compared with the control immersion, heat strain shortened reaction time in the first performance measurement period in the mornings and in the second measurement period in the afternoons. However, in light of the relatively small sample utilized in this experiment, it is probable that the interaction effects observed are not robust.

A number of investigators have reported that the effects of thermal stress on performance vary over the course of two to three hours exposure to heat (e.g. Mackworth, 1950; Bursill, 1958; Provins and Bell, 1970). However, several studies that have measured performance during similar periods of exposure to heat stress have found that performance is unaffected by the duration of the exposure (e.g. Wilkinson et al, 1964; Azer et al, 1972). The limited variation in performance with the duration of thermal strain observed in the present experiment may be due to the relatively short duration of the immersion (two and a quarter hours). It is possible that any duration-related effects of heat strain on performance become evident only over a period of several hours.

There was little evidence that the impact of thermal strain varied with the time of day at which the immersions were conducted. No two-way interactions between the condition and the time of day were observed. As described above, reaction time in the variable foreperiod simple reaction task was affected by an interaction between the time of day and the duration of heat strain. In the choice reaction task, accuracy was affected by an interaction of the condition, the time of day, and the order in which the performance tasks were administered. When the tasks were administered in a particular order (in which the choice reaction task was the fifth measure) accuracy in the afternoon immersion was poorer during thermal strain. However, given the relatively small sample tested, the interaction effects observed are unlikely to be robust.

Conclusions

The results of this experiment confirmed the principal finding of the first study; thermal strain produced a general increase in the speed of performance, without variation in accuracy. The increase in signal detection rate during thermal strain observed in the first experiment was not replicated. The absence of an effect of heat strain on signal detection rate appears to stem from the use of a substantially less demanding task than that administered in the previous study.

Tracking was unaffected by thermal strain. This result is at variance with previous research on the effects of heat stress on tracking, much of which has reported a deterioration in performance. The lack of variation in tracking with heat strain may be due to low task demand.

Performance in the immediate recall and recognition memory tasks did not vary significantly with thermal strain. It is probable that these measures were insufficiently sensitive to detect any variation in performance with heat strain in the relatively small sample tested.

There was little evidence that performance was affected by the duration of thermal strain. The absence of notable variation in performance with the duration of heat strain may be due to the relatively short duration of the immersion. Performance during thermal strain was largely unaffected by the time of day.

The Water Immersion Experiments: Summary and Critique

The principal strength of the water immersion technique was that it allowed body temperature to be maintained at a constant level of elevation with a high degree of precision. In ensuring consistency of thermal strain both across the participants and throughout performance measurement, the immersion experiments controlled a significant source of error in previous research on psychological performance in the heat. The most salient effect of heat strain was a general increase in the speed of performance, without variation in accuracy. It is conceivable that this effect is due, at least in part, to an increase in nerve conduction velocity and the speed of execution of motor responses. In the first experiment, an improvement in signal detection rate in a cognitive vigilance task was observed. This effect appears to reflect an increase in signal detectability, which may have its origin in an increase in the speed of information processing associated with elevation of body temperature. However, the effect was not replicated in the second experiment, in which a substantially less demanding vigilance task was utilized.

Selective attention, and immediate recall and recognition memory were unaffected by thermal strain. The absence of variation in memory with heat strain must be interpreted with caution, as the measures used may have been insensitive to any variation in performance in the relatively small sample tested. Compensatory tracking was also unaffected by thermal strain. This negative finding conflicts with the majority of previous research on psychomotor performance in the heat, which has reported a deterioration in performance.

The first experiment yielded some limited evidence of variation in performance over the course of the experimental immersion. An explicit aim of the second experiment was to investigate the impact of the duration of thermal strain. However, little evidence of variation in performance was obtained, perhaps due to the relatively short duration of the immersion. Performance during thermal strain was also largely unaffected by time of day.

The results of the immersion experiments do not support theoretical accounts of the relationship between heat and psychological performance proposed by previous investigators. Contrary to classic arousal theory, the first experiment found no evidence of consistent co-variation between subjective arousal and performance during thermal strain. The results of both experiments are incompatible with the proposal that elevation of core temperature increases the speed of performance whereas elevation of skin temperature impairs accuracy (Allnutt and Allan, 1973). During thermal strain, when both core and skin temperatures were elevated, the speed of performance was enhanced, but accuracy was unaffected.

A significant weakness of the water immersion technique is its lack of external validity. The thermal physiological response to warm water immersion is not comparable with that observed during exposure to thermally stressful air environments or during strenuous physical exercise. A notable difference is the restriction of sweating during water immersion. In addition, one of the explicit aims of the immersion experiments was to maintain core temperature at a specific, elevated value, but this stabilization of core temperature is not characteristic of the physiological response to environmental heat stress or strenuous exercise.

Directions for Subsequent Research

In light of the limited ecological validity of the immersion experiments, the focus of subsequent research was placed on the performance effects of more realistic sources of thermal strain. A third experiment was proposed, in which the participants were exposed to a thermally stressful air environment in a climatic chamber. The principal aim of this experiment was to assess whether the performance changes observed in the immersion experiments would generalize to conditions involving exposure to more realistic heat stress.

An additional aim of the third experiment was to examine the effects of prolonged thermal strain on performance. The impact of the duration of heat strain was specifically addressed in the second immersion experiment, but little evidence of variation in performance was observed, perhaps because of the relatively short duration of the immersion. Significant extension of the immersion period was constrained by practical considerations, in particular, the discomfort associated with prolonged confinement in the Jacuzzi bath. However, it is possible to expose volunteers to thermally stressful air environments in a climatic chamber for periods of several hours, allowing investigation of the effects of prolonged thermal strain on performance. The chamber experiment is described in Chapter 7.

The performance effects observed in the immersion experiments contrast with anecdotal evidence that suggests that thermal stress is commonly perceived to impair psychological performance. To compare the perceived effects of occupational exposure to heat stress with those measured in the laboratory a questionnaire was devised for administration in the field. The questionnaire was distributed to Royal Air Force personnel exposed to thermally stressful climatic conditions during overseas deployments. The survey is described in Chapter 6.

CHAPTER 6

The Perceived Effects of Thermal Stress on Performance

Introduction

In recognition of the limited external validity of the water immersion experiments, the focus of the later part of the research programme was directed towards the effects of more realistic sources of thermal strain on psychological performance. In contrast to the results of the immersion experiments, anecdotal evidence suggests that thermal stress is commonly perceived to impair performance. The aim of the present study was to measure the perceived effects of occupational exposure to heat stress in the field. A questionnaire was administered to Royal Air Force personnel exposed to hot climates during overseas deployments.

Method

Respondents

The respondents were aircrew and engineers from two Royal Air Force Tornado squadrons who were deployed to the Middle East from August to October 1996. One of the squadrons was based at Incirlik, on the southern Turkish coast. The second was deployed to Dhahran, on the Persian Gulf coast of Saudi Arabia.

Questionnaire

The questionnaire devised for the survey is shown in Appendix III. The first section sought demographic data. The initial questions in the main part of the questionnaire addressed factors that might, in principle, influence the perceived impact of thermal stress on performance, including the respondent's attitude to the climate, and the amount of work time spent out of doors (and therefore exposed to heat). Additional questions sought information about sources of thermal stress associated with flying. Question 7 elicited the respondent's perceptions of the effects of heat on a range of cognitive and psychomotor functions, including attention, reaction time, short term memory, and fine motor control. The respondent was also asked to describe any mood changes associated with exposure to heat.

A number of questions sought information about strategies for improving thermal comfort. These data are not presented here.

Procedure

One of the aircrew in each squadron volunteered to administer the survey. The survey was conducted during the hottest month of the deployment. To allow time for adaptation to time zone transitions and alterations in working practices the questionnaire was distributed during the second or third week overseas. An inevitable consequence of this timing was that the respondents would have undergone some acclimatization to the thermal environment.

Climatic data for the period during which the questionnaire was administered were sought from the meteorological service at each station.

Results

Meteorological Data

Table 6.1 shows the mean dry bulb temperature and relative humidity at dawn and midday at Incirlik and Dhahran. The data for Incirlik are the mean values recorded by the local meteorological service during the week in which the survey was conducted. Similar data for Dhahran could not be obtained; the data shown are the mean August values for Dhahran from 1974 to 1989 (data provided by the Meteorological Office). In the absence of information on variation in the data it was not possible to test for differences in the climatic conditions between the two locations. The dry bulb temperature was higher and the relative humidity was lower at Dhahran than at Incirlik.

	Incirlik		Dhahran	
	Dawn	Midday	Dawn	Midday
T_{db} (° C)	23	35	30	41
RH (%)	87	50	54	36

Table 6.1. Mean dry bulb temperature and relative humidity at dawn and midday at Incirlik and Dhahran

Survey Response Rates

At Incirlik, questionnaires were distributed to eleven aircrew and forty-eight engineers. The response rate in each group was one hundred percent. Two of the questionnaires returned by aircrew were not fully completed and these were excluded from analysis. At Dhahran, questionnaires were returned by twenty-two aircrew and fifty-four engineers. The response rates were not recorded. One of the questionnaires returned by an engineer was not completed fully and was excluded from analysis.

Attitudes to Heat

The respondents' attitudes to hot weather in general and to the local climatic conditions are shown in Table 6.2.

A chi-square test revealed no significant difference between the respondents at Incirlik and Dhahran in attitudes to hot weather in general. However, a greater proportion of the respondents based at Dhahran expressed a dislike of the local climate ($\chi^2 = 20.09$, $p < 0.001$; the percentages at Dhahran and Incirlik who disliked the local climate were 73% and 28%, respectively). There were no significant differences between the aircrew and engineers in attitudes to heat.

	Incirlik		Dhahran	
	Aircrew	Engineers	Aircrew	Engineers
In general, do you like hot weather?				
Yes	9 (100)	34 (71)	17 (77)	31 (59)
No	0 (0)	6 (12)	4 (18)	14 (26)
Neither like nor dislike it	0 (0)	8 (17)	1 (5)	8 (15)
Do you like the climate on this detachment?				
Yes	7 (78)	29 (60)	6 (27)	10 (19)
No	1 (11)	13 (27)	11 (50)	32 (60)
Neither like nor dislike it	1 (11)	6 (13)	5 (23)	11 (21)

Table 6.2. Attitudes to hot climates. The values shown are the number of respondents in each category. Percentages are shown in parentheses

Exposure to Thermal Stress

Table 6.3 shows the mean number of working hours that the respondents spent indoors and out of doors. As the reported length of the working day varied across the respondents, mean percentages are also presented.

Incirlik		Dhahran	
Aircrew	Engineers	Aircrew	Engineers
Out of doors, without shade			
2.1 (1.4) 20%	4.0 (1.5) 40%	1.0 (0.9) 8%	2.5 (1.6) 22%
Out of doors, in the shade			
0.7 (0.7) 6%	2.0 (1.8) 19%	1.1 (1.0) 9%	3.7 (2.1) 32%
Indoors, without air conditioning			
1.3 (1.5) 11%	3.1 (2.2) 28%	0.3 (0.6) 2%	0.6 (1.2) 5%
Indoors, with air conditioning			
3.9 (2.6) 34%	1.4 (1.7) 13%	6.8 (2.4) 54%	4.9 (3.0) 41%
Flying			
2.9 (0.2) 29%	n/a	3.4 (0.8) 27%	n/a

Table 6.3. Mean number of working hours spent out of doors with and without shade, indoors with and without air conditioning, and flying. Standard deviations are shown in parentheses

Analysis of variance was conducted to identify any effects of occupation and geographical location on the proportion of work time spent out of doors. The percentage of time spent outside was affected by occupation ($F = 70.70$, $df = 1, 128$, $p < 0.001$); the engineers spent more time out of doors than the aircrew (see Table 6.4).

	Aircrew	Engineers	Mean
Incirlik	26 (13)	60 (18)	43 (16)
Dhahran	17 (13)	53 (22)	35 (18)
Mean	22 (13)	57 (20)	

Table 6.4. Mean percentage of work time spent out of doors. Standard deviations are shown in parentheses

The majority of the aircrew (seventy-four percent) reported that, in general, they were thermally comfortable while flying. The remainder indicated that they felt uncomfortably hot. Ninety-five percent of the aircrew identified the period prior to take-off as particularly uncomfortable. This discomfort was associated with the conduct of external aircraft checks (which can involve relatively strenuous activity) in full sunshine while wearing several layers of protective clothing, and with the limited cockpit air conditioning available while the aircraft is on the ground.

The Effects of Thermal Stress on Mood

Forty-two percent of the respondents reported changes in mood that they associated with the heat. The most commonly cited change in affect was increased irritability; seventy-six percent of those who reported mood changes indicated that they felt more irritable, short-tempered, and intolerant. Thirty-eight percent reported feeling lethargic in the heat. These effects are consistent with the increase in Anger/Frustration and the decrease in Energetic Arousal observed during thermal strain in the immersion experiments. One respondent reported feeling depressed.

A chi-square test revealed no significant difference between the proportions of aircrew and engineers reporting mood changes. A greater proportion of the respondents based at Dhahran reported changes in mood ($\chi^2 = 13.35$, $p < 0.001$; the percentages at Dhahran and Incirlik who reported mood change were 56% and 23%, respectively). This effect may reflect the hotter conditions at Dhahran. In addition, as noted above, a greater proportion of the respondents at Dhahran expressed a dislike of the local climate. A chi-square test indicated that those respondents who disliked the local conditions were more likely to report mood change ($\chi^2 = 21.73$, $p < 0.001$; 63% who disliked the local climate reported changes in mood compared with 17% of those who liked the local conditions). The occurrence of mood change did not vary significantly with attitudes to hot weather in general.

The Perceived Effects of Thermal Stress on Psychological Performance

The perceived effects of heat on performance are shown in Table 6.5. A notable finding was that none of the respondents reported that performance improved in the heat.

The perceived effect of heat on reaction time differed between the aircrew and engineers ($\chi^2 = 7.68$, $p < 0.01$). Impairment of reaction time was reported by one third of the aircrew and two-thirds of the engineers. No other significant differences between the two groups in the perceived effects of heat on performance were found. The reported effects of heat did not vary significantly with geographical location. Accordingly, the data for all of the respondents were combined for further analysis.

The number of respondents who reported that performance was impaired in the heat and the number who indicated that performance was unaffected were compared using binomial tests. Significantly more respondents reported that sustained concentration deteriorated in the heat ($p < 0.001$). This finding contrasts with the absence of variation in attention with thermal strain in the first immersion experiment. Fine motor control and physically strenuous work were also perceived to be impaired in the heat ($p < 0.05$ and $p < 0.001$, respectively). Significantly more respondents reported that short term memory and mental arithmetic were unaffected by heat stress

($p < 0.001$ for both functions). The former result is consistent with the lack of variation in immediate recall in the second immersion experiment.

	Don't Know / Not Applicable	Better in Heat	Unchanged in Heat	Worse in Heat
Sustained concentration	7 (5)	0	39 (30)	86 (65)
Speed of reactions	12 (9)	0	50 (38)	70 (53)
Keeping information in memory for short periods	8 (6)	0	99 (75)	25 (19)
Mental alertness	8 (6)	0	69 (52)	55 (42)
Ability to do mental calculations	9 (7)	0	91 (69)	32 (24)
Ability to resist distraction	15 (11)	0	63 (48)	54 (41)
Ability to do delicate manual tasks	11 (8)	0	48 (37)	73 (55)
Ability to do physically strenuous work	5 (4)	0	5 (4)	122 (92)

Table 6.5. Perceived effects of thermal stress on performance. The values shown are the number of respondents in each category. Percentages are shown in parentheses

Mood Change and Performance during Thermal Stress

A greater proportion of the respondents who experienced changes in mood reported that reaction time was impaired in the heat ($\chi^2 = 6.26$, $p < 0.05$; 77% of those who reported mood change indicated that reaction time deteriorated compared with 53% who did not report mood change). In addition, a greater proportion of those who reported mood change indicated that sustained concentration deteriorated in the heat ($\chi^2 = 4.52$, $p < 0.05$; 80% of those who experienced changes in mood reported impairment of concentration compared with 61% who did not report mood change). These findings contrast with the results of the first immersion experiment, in which there was little evidence of association between mood and performance during thermal strain.

Attitudes to Heat and Performance during Thermal Stress

A greater proportion of the respondents who disliked the local climate reported that heat increased distractibility ($\chi^2 = 6.92$, $p < 0.01$; 64% of those who disliked the local conditions indicated that resistance to distraction was impaired compared with 35% who liked the local climate). Those who disliked the local climate were also more likely to report impairment of mental alertness ($\chi^2 = 5.63$, $p < 0.05$; 64% of those who disliked the local climate reported that mental alertness deteriorated compared with 39% who liked the local conditions). The perceived effects of heat on performance did not vary with attitudes to hot weather in general.

Discussion

This study identified a number of changes in mood and psychological performance associated with occupational exposure to thermal stress.

Approximately forty percent of the respondents experienced changes in mood that they attributed to the heat. The principal mood changes reported were increased irritability and lethargy. These findings are consistent with the increase in Anger/Frustration and the reduction in Energetic Arousal observed during thermal strain in the immersion experiments. There was evidence that the occurrence of mood change was associated with the severity of the climatic conditions and with attitudes to the conditions. Changes in mood were more common at Dhahran, where the air temperature was higher than at Incirlik. A greater proportion of the respondents who disliked the local climatic conditions reported changes in mood. The occurrence of mood change did not appear to be influenced by the duration of exposure to thermal stress. There was no significant difference in the prevalence of mood change between the aircrew and the engineers, in spite of the fact that the latter group was exposed to heat for a greater portion of the working day.

It was notable that none of the respondents reported that heat enhanced psychological performance. This contrasts with the general increase in the speed of performance observed in the immersion experiments. Heat stress was reported to impair sustained concentration and fine motor control. The perceived deterioration in concentration is inconsistent with the absence of variation in selective attention observed in the first immersion experiment. Fine motor control was not assessed in the immersion studies, and there is a dearth of data on the effects of thermal stress on fine motor control in the literature. Lovingood et al (1967) reported that heat stress enhanced fine motor control.

Short term memory and mental arithmetic were reported to be unaffected by heat. The former finding is consistent with the absence of variation in the immediate recall task observed in the second immersion experiment and with the results reported by Holland et al (1985). The research literature on the effects of heat on mathematical reasoning yields a largely contradictory pattern of findings.

The limited differences between the aircrew and the engineers in the reported effects of heat stress on performance suggests that performance change was largely unaffected by the duration of exposure to heat during the working day. A greater proportion of the engineers reported that reaction time deteriorated in the heat, but no other differences between the aircrew and engineers in the perceived effects of heat were evident.

There was some evidence of an association between mood and performance change in the heat. A greater proportion of the respondents who experienced mood change reported that reaction time and sustained concentration deteriorated in the heat. These findings contrast with the very limited evidence of covariation between mood and performance found in the first immersion experiment. Performance change in the heat was also associated with attitudes to the local climatic conditions. A greater proportion of the respondents who expressed a dislike of the local climate reported that heat increased distractibility and impaired mental alertness.

Conclusions

This study identified a number of differences between the effects of thermal strain on performance observed in the immersion experiments and the perceived effects of thermal stress in the field. The immersion experiments allowed a significant source of error in previous research to be controlled, at the cost of ecological validity. The principal effect of thermal strain observed in these experiments was an enhancement of the speed of performance. None of the respondents in the questionnaire survey reported that thermal stress improved performance. Heat stress was perceived to impair sustained concentration, fine motor control, and physically strenuous activity.

Subjective assessments of psychological performance are not, of course, necessarily consistent with objective measures. A number of investigators have reported discrepancies between the perceived and objective effects of stressors on performance (e.g. Poulton, 1977; Yesavage and Leirer, 1986). In the present study, the psychological effects attributed by the respondents to heat stress may have been influenced by other factors associated with deployment overseas, including changes in working practices and disruption of personal life. The clear differences between the performance changes observed in the immersion experiments and the perceived effects of thermal stress reinforced the need for an experiment in an ecologically more valid environment free of uncontrolled, extraneous variables. Accordingly, a climatic chamber experiment was conducted to investigate the extent to which the findings of the immersion experiments would generalize to conditions involving exposure to a more realistic source of thermal strain.

CHAPTER 7

Experiment 3

Introduction

The water immersion experiments allowed the identification of consistent and replicable changes in psychological performance during precisely controlled thermal strain. However, given the limited external validity of these experiments, it was important to establish whether the findings would generalize to conditions involving exposure to more realistic sources of heat strain. This was the principal objective of the final experiment, in which volunteers were exposed to a thermally stressful air environment in a climatic chamber.

In addition to its greater ecological validity, the climatic chamber experiment also allowed the effects of the duration of thermal strain to be investigated more fully than had been possible using the water immersion technique. The impact of the duration of heat strain had been addressed explicitly in the second immersion experiment, but little variation in performance had been evident, perhaps due to the relatively short duration of the immersion (two and a quarter hours). Practical considerations prevented significant extension of the immersion period. However, as it is possible to expose volunteers to a stressful air environment in a climatic chamber for a period of several hours, the chamber experiment permitted examination of the impact of prolonged heat strain on performance.

The survey of Royal Air Force personnel during overseas deployments revealed some deterioration in self-assessed psychological performance associated with exposure to thermal stress. These findings contrast with the performance effects observed in the immersion experiments. To compare the perceived and objective effects of thermal stress in a realistic but controlled environment the participants in the climatic chamber experiment were requested to assess the impact of heat on their performance.

Selection of the Performance Measures

The performance tasks were selected from those used in the water immersion experiments. The tasks chosen included several that had revealed significant effects of thermal strain and a number in which performance had been unaffected. The tasks repeated from the first immersion experiment were the focused attention and categoric search tasks, and the cognitive vigilance task. Those repeated from the second experiment were the immediate recall and recognition memory tasks. The fixed and variable foreperiod simple reaction tasks, and the verbal reasoning task, which had been utilized in both of the immersion experiments, were also administered.

Selection of the Environmental Conditions

The environmental conditions for the control and experimental exposures were selected on the basis of modelling of the thermoregulatory response to thermally stressful air environments using the Loughborough University of Technology computer-based model of thermoregulation (Haslam and Parsons, 1994; the modelling was conducted by the Statistics and Mathematical Modelling section of the Centre for Human Sciences). The aim was to identify the climatic conditions that would ensure maximal elevation of core temperature in the experimental exposure, but without exceeding local ethics limits (i.e. a rectal temperature value of 38.5° C, or 39° C in 'experienced' participants). The following assumptions were made:

> The participants would be exposed to thermal stress for a period of six hours. This was the maximum period of exposure that was practical within the working day, allowing time for the preparation and recovery of the participants.

The participants would wear a standardized clothing assembly (consisting of Royal Air Force flying clothing) of known insulation and evaporative resistance (1.37 clo and 0.03 kPa/m^2/W, respectively).

The participants would not engage in strenuous exercise during the chamber exposures. The mean metabolic rate of the participants during experimentation was assumed to be 100 W/h.

In addition to these assumptions, it was known that the air movement in the climatic chamber could not be varied, and was fixed at approximately 0.3 m/s.

On the basis of modelling, the environmental conditions selected for the experimental exposure were 36.5° C T_{db}, with 80% rh. The conditions selected for the control exposure were 24.5° C T_{db}, with 40% rh.

Method

Participants

The participants were sixteen male members of the staff of the Centre for Human Sciences, who volunteered to take part in the experiment. The participants ranged in age from twenty to thirty-nine years, with a mean age of thirty years. Prior to the experiment, each volunteer underwent a medical examination and gave written consent to participate in the study.

Design

A repeated-measures design was used in which each participant completed a control and an experimental test session. In each session, the participant completed a battery of performance tasks on five occasions: once in a thermoneutral environment to obtain baseline data and on four occasions during a six-hour period in the chamber.

In the control condition, the chamber climatic conditions were 24.5° C T_{db}, with 40% rh. In the experimental condition, the climatic conditions were 36.5° C T_{db}, with 80% rh. The air velocity in both conditions was approximately 0.3 m/s. The chamber exposures were conducted between 1000 and 1600 h. To identify any effects of the duration of the testing session during exposure to thermal stress one half of the sample completed the performance tasks in a specific order and the remainder completed the tasks in the reverse order. There was an interval of one day between each participant's test sessions. The order of exposure to the two conditions was balanced across the participants.

Tests and Measures

Environmental Measures

The dry bulb temperature and relative humidity in the climatic chamber were measured using a dry bulb temperature and relative humidity probe (Type 0636-9767, Testo Ltd.). Air movement was measured with an anemometer (Type 0635-9640, Testo Ltd.). The environmental data were recorded at intervals of five minutes using a data logger (Type 454, Testo Ltd.).

The dry bulb temperature and relative humidity in the room in which the baseline performance testing was conducted were measured using a dry bulb temperature and relative humidity probe (Kane-May Ltd.). The data were recorded at intervals of five minutes using a data logger (Type KM1241, Kane-May Ltd.).

Physiological Measures

The physiological variables measured were rectal and skin temperatures, heart rate, sweat secretion, and salivary cortisol level. Rectal temperature was measured using a rectal thermistor (Fenwal Type UUA 32J2, Edale Instruments Ltd.) inserted 15 cm beyond the anal margin. Skin temperature was measured with skin thermistors

(Fenwal Type UUA 32J2, Edale Instruments Ltd.) at five sites: the chest, upper arm, thigh, calf, and cheekbone. Heart rate was measured with three Ag/AgCl ECG electrodes. Sweat secretion was measured by calculating the difference between the participant's nude weight before and after the chamber exposure (measured using a Type 824J balance, Fereday Ltd.), adjusted for the weights of food and fluids consumed (measured using a Type LC4800P balance, Sartorius AG) and excreta voided. Rectal and skin temperatures were recorded at two-minute intervals using a data logger (400 series Data Acquisition and Control System, Anville Instruments) controlled by an IBM-compatible personal computer. Heart rate was displayed on an ECG monitor (Athena Type 9040, Artema Ltd.) and was recorded manually at five-minute intervals.

Saliva samples were collected on nine occasions during each test session and were assayed for cortisol. The method used to collect saliva is described in Chapter 4.

Psychological Performance Measures

Psychological performance was measured using a battery of eight tasks. The tasks were controlled by an IBM-compatible personal computer, with stimuli displayed on a VGA monitor. Responses were made using a console connected to the computer.

Three of the performance tasks were repeated from the first immersion experiment: the cognitive vigilance task, and the focused attention and categoric search tasks (for details, see Chapter 4). The immediate recall and recognition memory tasks were repeated from the second experiment (see Chapter 5). In addition, the fixed and variable foreperiod simple reaction tasks, and the verbal reasoning task, which had been used in both of the immersion experiments, were administered (see Chapter 4). As in the first experiment, the variable foreperiod simple reaction task was presented at the beginning and repeated at the end of the performance battery to explore any effects of the duration of the testing session on performance.

Subjective Measures

Mood

As in the immersion experiments, mood was measured using the UMACL (Matthews et al 1990; see Chapter 4 for details).

Thermal comfort

As in the previous experiments, thermal comfort was measured using a nine point rating scale ranging from 'unbearably cold' (-4), through 'comfortable' (0), to 'unbearably hot' (4).

Perceived Impact of Heat on Psychological Performance

The perceived impact of thermal stress on performance was measured using a seven point rating scale ranging from 'heat greatly impairs performance' (1), through 'heat has no effect on performance' (4), to 'heat greatly improves performance' (7).

Procedure

A few days before his first test session, each participant completed a performance practice session in which the task battery was completed three times.

The participants were requested to avoid alcohol for twenty-four hours before their test sessions. None of the participants smoked tobacco.

The participants were tested in groups of four. The participants reported at 0830 h to an air-conditioned preparation room. The mean values of T_{db} and % rh in the preparation room were 23° C (s.d. = 0.5° C) and 43% rh (s.d. = 3%), respectively. Following insertion of the rectal thermistor, each participant was weighed wearing his underwear. The participants were instrumented with the skin thermistors and ECG electrodes, and they donned a standardized clothing assembly of known insulation, comprised of Royal Air Force flying clothing. The clothing consisted of cotton long johns, a cotton, long-sleeved, roll-neck 'T' shirt, a flying coverall, terry-loop socks, and flying boots. At 0915 h, physiological data recording was started, mood and thermal comfort measurements were made, and saliva samples were collected. The performance tasks were then administered to collect baseline data; the battery took approximately thirty minutes to complete. The participants were screened from one another by partitions during performance testing. One half of the sample completed the tasks in the following order: immediate recall, simple reaction time (variable foreperiod), vigilance, focused attention, categoric search, simple reaction time (fixed foreperiod), verbal reasoning, simple reaction time (variable foreperiod), and recognition memory. The remaining participants also completed the immediate recall and recognition memory tasks first and last, respectively, but the intervening tasks were completed in the reverse order. On completion of baseline performance measurement, physiological data recording was stopped.

At 1000 h, the participants entered the climatic chamber and physiological data logging was resumed. The performance tasks were administered on four occasions, beginning at 1030 h, 1145 h, 1400 h, and 1515 h. The participants were screened from one another by partitions while completing the tasks. To protect the computer equipment used to control the performance tasks from the environmental conditions in the chamber the processor units and monitors were housed in wooden boxes fitted with Perspex sides and cooled with compressed air (see Figure 7.1). The response consoles were waterproof.

Mood and thermal comfort measurements were taken and saliva samples were collected immediately before and after each performance measurement period.

Between the performance measurement periods, the participants sat in armchairs, reading if they chose. The physiological instrumentation leads were sufficiently long to allow the participants to move around the climatic chamber, as they chose.

Figure 7.1. Equipment for measuring psychological performance

At 1230 h, the participants were given a light lunch consisting of sandwiches, fruit, and biscuits. Those participants who habitually did not eat lunch were asked to abstain from lunch during the experiment. To reduce post-prandial effects on performance in the early afternoon the participants were requested to complete lunch by 1300 h, one hour before the performance tests were administered. The participants were permitted to drink cooled water and fruit squash *ad libitum* throughout the chamber exposures.

The weights of food and fluids consumed by each participant were recorded. The participants were weighed before and after using the toilet (which was located within the chamber).

On completion of the final mood and comfort measurements, and collection of the final saliva samples (at 1600 h, approximately), physiological data logging was stopped. The participants returned to the preparation room and undressed. Following removal of the skin thermistors and ECG electrodes, each participant was weighed in his underwear.

On completion of the experiment, each participant was requested to rate the impact of heat on his performance.

Results

Two participants withdrew from the experimental condition, one on completing three hours and forty-five minutes of the exposure, the second on completing four hours of the exposure. Both reported intolerable discomfort as the reason for withdrawal. These participants' data were excluded from inferential statistical analysis.

Environmental Data

In the control condition, the mean dry bulb temperature was 24.8° C (s. d. = 0.4° C), and the mean relative humidity was 40.8% (s. d. = 1.1%). In the experimental condition, the mean dry bulb temperature was 36.4° C (s. d. = 0.1° C), and the mean relative humidity was 79.7% (s. d. = 1.3%). The air velocity in both conditions was approximately 0.3 m/s.

Physiological Data

Body Temperatures, Heart Rate, and Sweat Secretion

The analysis of the rectal and skin temperature, and heart rate data focused on those periods in each test session during which psychological performance was measured. As skin temperature typically varies between the torso and limbs during exposure to air, the mean temperature of these sites was calculated using Ramanathan's formula (Ramanathan, 1964). The core and skin temperature data were analysed using repeated-measures analysis of variance. The independent variables included in the analysis were the condition and the measurement period. Significant effects were analysed further using the Newman-Keuls range test and Bonferroni *t* test.

The volumes of sweat secreted in the control and experimental exposures were compared using a repeated-measures *t* test.

The Thermal Physiological Response to the Experimental Condition

In each of the four performance measurement periods conducted in the climatic chamber, rectal temperature was higher in the experimental than the control condition ($p < 0.001$ for all comparisons; mean values are shown in Table 7.1). Ramanathan mean skin temperature, cheek temperature, and heart rate were elevated in the heat ($p < 0.001$ for all comparisons, and all variables; see Tables 7.2 – 7.4). The volume of sweat secreted was greater in the experimental than the control condition ($t = 6.13$, $df = 13$, $p < 0.001$; see Table 7.5).

Body temperatures and heart rate were affected by the duration of exposure to heat; thermal strain increased over the course of the experimental exposure. Skin temperatures and heart rate were higher during the first and second performance measurement periods than during the baseline period ($p < 0.001$ for all variables; Tables 7.2 – 7.4). Heart rate increased from the first to the second performance measurement period ($p < 0.001$; see Table 7.4). Significant elevation of core temperature became evident in the second performance measurement period; the mean rectal temperature during this period was greater than the values recorded during the baseline and the first performance measurement periods ($p < 0.001$ for both comparisons; see Table 7.1 and Figure 7.2). Thermal strain intensified in the final two hours of the exposure to heat. Rectal temperature, skin temperatures, and heart rate were higher during the third and the final performance measurement periods than during the baseline period, and the first and second measurement periods ($p < 0.001$ for all comparisons, and all variables; see Tables 7.1 – 7.4).

The Thermal Physiological Response to the Control Condition

A slight but significant decline in rectal temperature from its baseline value was evident during the first and second performance measurement periods in the control exposure ($p < 0.001$ for both comparisons; see Table 7.1 and Figure 7.2). Rectal temperature rose during the latter portion of the exposure, reflecting the normal circadian increase in core temperature in the afternoon. The value of rectal temperature during the third performance measurement period was lower than that during the baseline period ($p < 0.05$) but higher than that during the second performance measurement period ($p < 0.05$). Rectal temperature was higher during the final than during the second performance measurement period ($p < 0.01$).

The absence of the normal circadian increase in core temperature during the morning period of the control exposure may reflect a reduction in metabolic rate due to the relative inactivity of the participants. However, it is notable that the Ramanathan mean skin temperature was significantly higher during each of the four performance measurement periods than during the baseline period ($p < 0.001$ for all comparisons; see Table 7.2). This increase in skin temperature may reflect the higher dry bulb temperature in the climatic chamber compared with that in the preparation room in which the baseline performance testing was conducted. The preparation room was air-conditioned, but the climatic conditions could not be controlled as precisely as those in the climatic chamber; the mean values of T_{db} in the preparation room and the climatic chamber were 23° and 24.8° C, respectively. It is possible that the slight decline in rectal temperature during the morning period of the exposure may have stemmed from a redistribution of the body's heat associated with elevation of skin temperature. Scrutiny of the thermal comfort ratings yielded no evidence of an associated change in subjective comfort (see Table 7.8).

Cheek skin temperature did not vary significantly across the baseline and the chamber performance measurement periods.

Heart rate varied over the course of the control exposure. Heart rate was lower during the second performance measurement period than during the baseline period ($p < 0.001$), the first and the final performance measurement periods ($p < 0.01$ for both comparisons), and the third performance measurement period ($p < 0.001$; see Table 7.4). In addition, heart rate was lower during the first and the final performance measurement periods than during the baseline and the third measurement periods ($p < 0.05$ for all comparisons).

The Baseline Period

There were no significant differences between the control and experimental sessions in rectal temperature, skin temperatures or heart rate during the baseline period.

	Control Session	Experimental Session
Baseline	36.95 (0.25)	36.97 (0.26)
First Performance Assessment	36.73 (0.27)	37.00 (0.29)
Second Performance Assessment	36.68 (0.26)	37.34 (0.29)
Third Performance Assessment	36.81 (0.19)	38.01 (0.37)
Fourth Performance Assessment	36.85 (0.15)	38.11 (0.37)

Table 7.1. Mean rectal temperature (° C) during baseline performance testing and during performance testing in the climatic chamber. Standard deviations are shown in parentheses

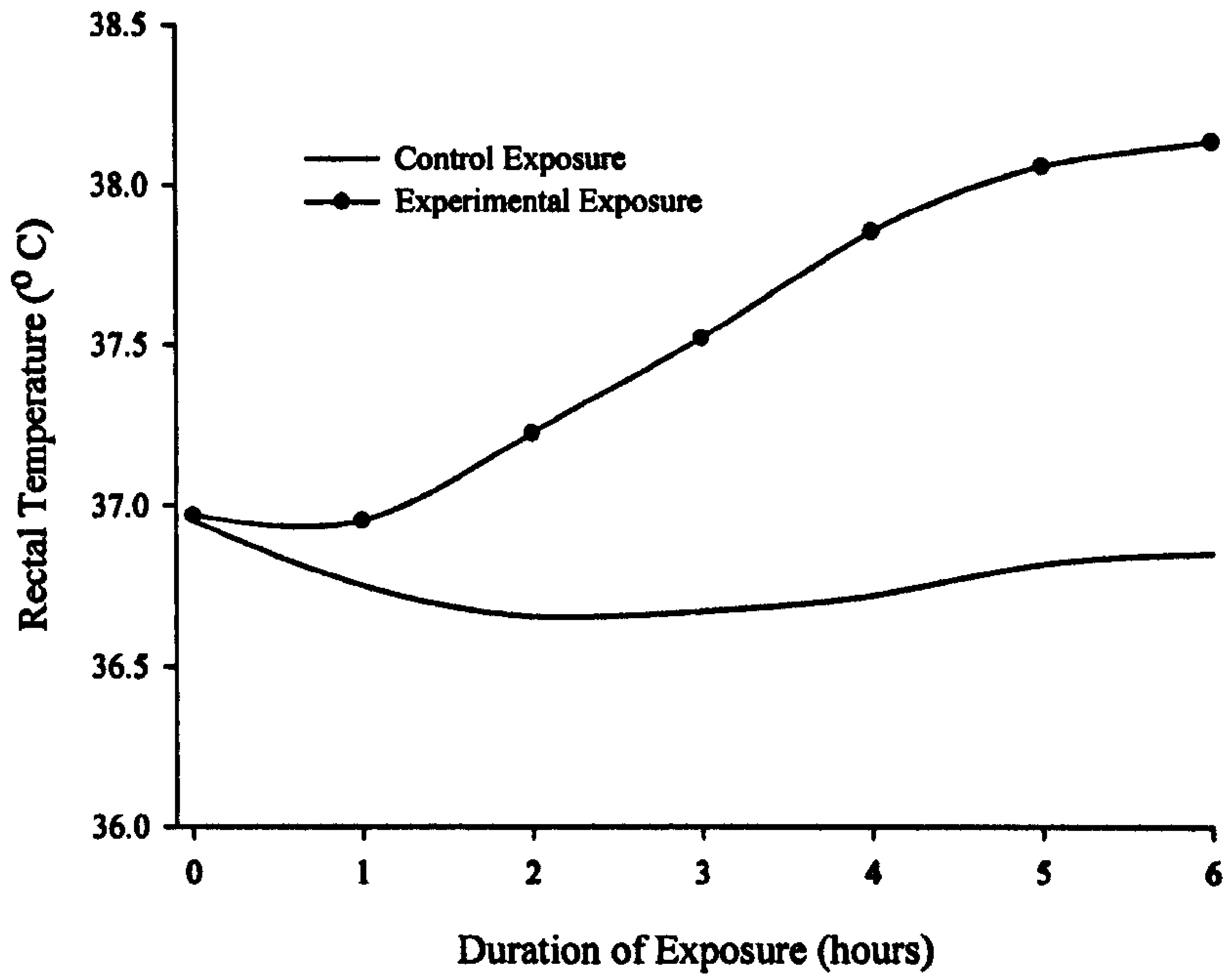

Figure 7.2. Mean rectal temperature during the control and experimental exposures

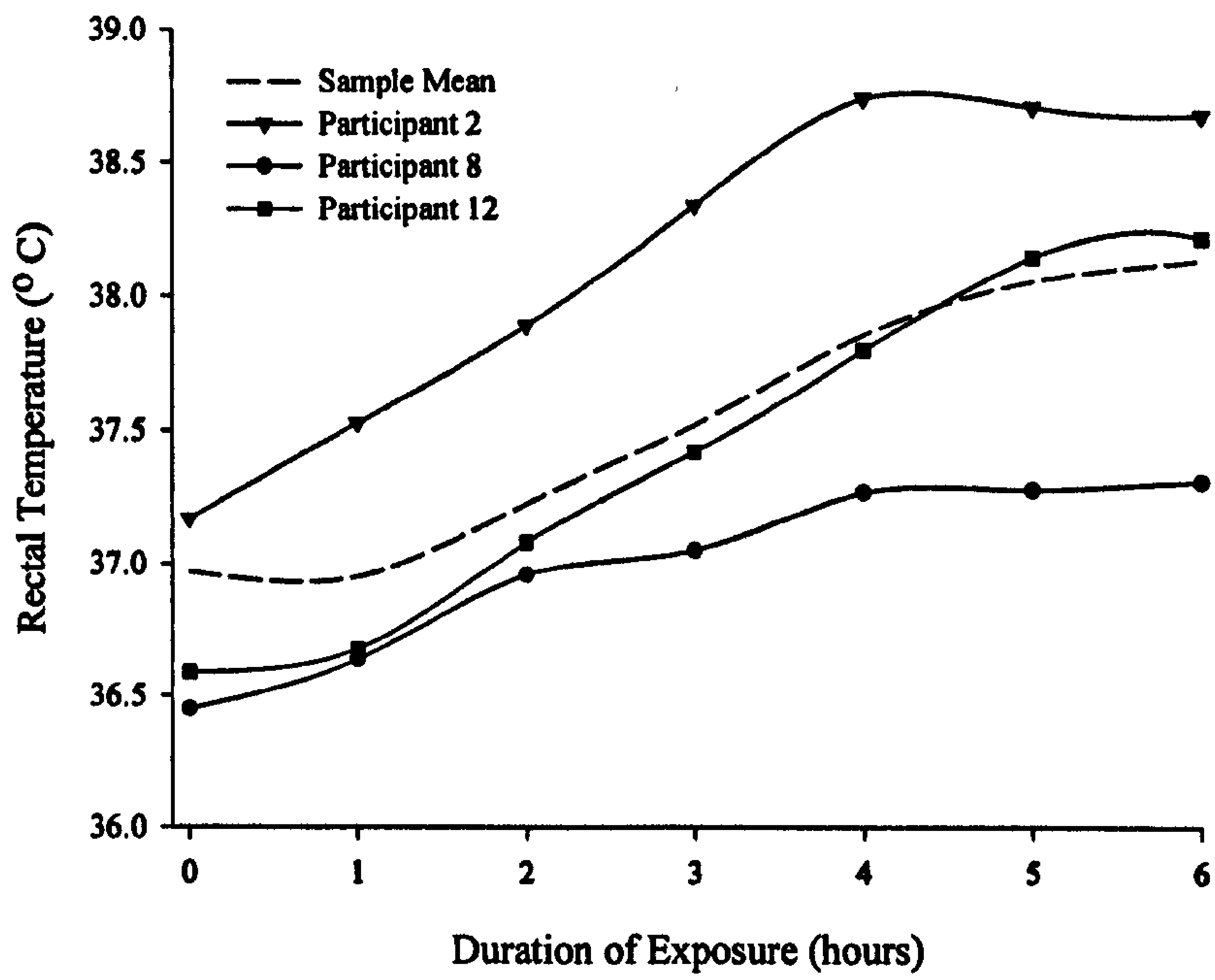

Figure 7.3. Rectal temperature response of three participants during the experimental exposure. The graph illustrates the individual variation in core temperature response characteristic of exposure to thermally stressful air environments

	Control Session	Experimental Session
Baseline	33.85 (0.62)	33.78 (0.57)
First Performance Assessment	34.30 (0.48)	36.47 (0.24)
Second Performance Assessment	34.30 (0.42)	36.52 (0.30)
Third Performance Assessment	34.40 (0.36)	36.99 (0.39)
Fourth Performance Assessment	34.48 (0.33)	37.06 (0.50)

Table 7.2. Mean value of the Ramanathan mean skin temperature (° C) during baseline performance testing and during performance testing in the climatic chamber. Standard deviations are shown in parentheses

	Control Session	Experimental Session
Baseline	33.68 (0.71)	33.12 (0.65)
First Performance Assessment	34.04 (0.58)	36.15 (1.30)
Second Performance Assessment	33.83 (0.64)	36.35 (1.35)
Third Performance Assessment	33.82 (0.67)	36.84 (1.58)
Fourth Performance Assessment	33.87 (0.74)	36.93 (1.44)

Table 7.3. Mean cheek temperature (° C) during baseline performance testing and during performance testing in the climatic chamber. Standard deviations are shown in parentheses

	Control Session	Experimental Session
Baseline	73 (11)	74 (14)
First Performance Assessment	69 (11)	80 (15)
Second Performance Assessment	65 (11)	91 (14)
Third Performance Assessment	74 (11)	113 (19)
Fourth Performance Assessment	70 (11)	111 (17)

Table 7.4. Mean heart rate (beats per minute) during baseline performance testing and during performance testing in the climatic chamber. Standard deviations are shown in parentheses

Control Exposure	Experimental Exposure
0.45 (0.33)	1.66 (0.78)

Table 7.5. Mean volume of sweat secreted (L) in the control and experimental exposures. Standard deviations are shown in parentheses

Salivary Cortisol

The salivary cortisol data were analysed using repeated-measures analysis of covariance, with the baseline value treated as a covariate. The data were transformed to meet the assumptions of parametric testing. The independent variables included in the analysis were the condition, the duration of the exposure, and the order of exposure to the two conditions. Mean salivary cortisol concentrations are shown in Table 7.6; the means have been adjusted on the basis of baseline values, and back-transformed and corrected for bias.

Salivary cortisol concentration was affected by the duration of the chamber exposure ($F = 2.24$, $df = 7, 70$, $p < 0.05$), and by an interaction between the condition and the duration of the exposure ($F = 4.25$, $df = 7, 70$, $p < 0.001$). Analysis of this interaction effect revealed variation in cortisol level with the duration of the exposure to heat. In the hot exposure, cortisol concentration was higher on completion of the final performance measurement period than before the first measurement period ($p < 0.01$), after the first measurement period ($p < 0.001$), before the second measurement period ($p < 0.001$), and after the second measurement period ($p < 0.01$). Cortisol levels before and after the third performance measurement periods, and before the final measurement period were greater than that recorded after the first measurement period ($p < 0.05$ for all comparisons). No significant variation in cortisol level with the duration of the control exposure was evident. On completion of the final performance assessment, cortisol concentration was higher in the experimental than the control exposure ($p < 0.01$).

	Control Exposure	Experimental Exposure
Before First Performance Session	2.04 (1.45)	1.99 (1.59)
After First Performance Session	2.19 (1.16)	1.05 (1.79)
Before Second Performance Session	2.35 (1.14)	1.52 (1.88)
After Second Performance Session	1.72 (1.57)	1.63 (0.93)
Before Third Performance Session	2.71 (1.60)	2.91 (1.61)
After Third Performance Session	2.57 (2.23)	3.18 (3.04)
Before Fourth Performance Session	1.71 (1.19)	3.72 (3.08)
After Fourth Performance Session	1.19 (1.58)	6.14 (4.95)
Mean	2.06 (1.49)	2.77 (2.36)

Table 7.6. Mean salivary cortisol concentration (nmol/L). Standard deviations are shown in parentheses

Subjective Data

Mood

Scores on the Energetic Arousal, Tense Arousal, Hedonic Tone, and Anger/Frustration scales of the UMACL were analysed using repeated-measures analysis of covariance, with baseline values treated as covariates. The independent variables included in the analysis were the condition, the duration of the exposure, and the order of exposure to the two conditions. Where necessary, the data were transformed to meet the assumptions of parametric testing. Significant effects were analysed further using the Newman-Keuls range test and Bonferroni *t* test. Mean values are shown in Table 7.7; these have been adjusted on the basis of baseline performance, and, where applicable, have been back-transformed and adjusted for bias.

Energetic Arousal was affected by the duration of the chamber exposure ($F = 10.78$, $df = 7, 77$, $p < 0.001$), and by an interaction between the condition and the duration of the exposure ($F = 8.11$, $df = 7, 77$, $p < 0.001$). Analysis of this interaction effect revealed that arousal varied over the course of the exposure to heat, with a decrease in arousal evident in the final two hours of the exposure. In the heat, arousal was higher before and after the first performance measurement period than before the third measurement period ($p < 0.05$ for both comparisons), after the third measurement period, and before and after the final measurement period ($p < 0.001$ for all comparisons). The arousal score recorded before the second performance measurement period was higher than those observed after the third measurement period, and before and after the final measurement period ($p < 0.001$ for both comparisons). The rating observed after the second performance measurement period was higher than those recorded after the third measurement period and before the last measurement period ($p < 0.05$ for both comparisons), and after the final assessment ($p < 0.01$). No significant variation in arousal over the course of the control exposure was evident. Comparison of the arousal ratings between the control and experimental exposures indicated that the ratings recorded before and after the final performance measurement period were lower in the heat ($p < 0.01$ for both comparisons).

Tense Arousal was affected by the condition ($F = 12.21$, $df = 1, 10$, $p < 0.01$), the duration of the chamber exposure ($F = 5.11$, $df = 7, 77$, $p < 0.001$), and by an interaction between these two variables ($F = 2.15$, $df = 7, 77$, $p < 0.05$). Analysis of this interaction indicated that tension scores varied over the course of the exposure to heat. In the experimental exposure, tension ratings before the third and before the final performance measurement periods (the ratings were of identical value) were higher than those recorded before the first performance measurement period ($p < 0.01$), and before and after the second measurement periods ($p < 0.01$ and $p < 0.05$, respectively). No significant variation in tension during the control exposure was observed. Comparison of tension ratings between the control and experimental exposures indicated higher ratings in the heat after the third performance measurement period ($p < 0.01$), before the final measurement period ($p < 0.05$), and after the final measurement period ($p < 0.01$).

Hedonic Tone was affected by the duration of the chamber exposure ($F = 5.93$, $df = 7, 70$, $p < 0.001$), and by an interaction between the condition and the duration of the exposure ($F = 2.77$, $df = 7,70$, $p < 0.05$). Analysis of this interaction revealed that Hedonic Tone ratings varied over the course of the exposure to heat, with lower scores evident towards the end of the exposure. In the heat, the rating recorded after the third performance measurement period was lower than those observed before and after both the first and second measurement periods ($p < 0.01$ for all comparisons). The rating observed after the final measurement period was lower than those recorded before and after both the first and second measurement periods ($p < 0.001$ for all comparisons). In addition, the rating recorded on completion of the final performance measurement period was lower than those observed before the third and before the final measurement periods ($p < 0.05$ for both comparisons). No significant variation over the course of the control exposure was evident. Comparison of the Hedonic Tone scores between the control and experimental exposures indicated that the rating recorded on completion of the final performance assessment was lower in the heat ($p < 0.01$).

	Before Performance 1	After Performance 1	Before Performance 2	After Performance 2	Before Performance 3	After Performance 3	Before Performance 4	After Performance 4	Mean
Energetic Arousal									
Control	23.8 (3.1)	21.6 (4.7)	22.6 (3.7)	22.0 (5.4)	20.8 (4.4)	20.9 (4.5)	22.4 (4.1)	23.0 (4.4)	22.1 (4.3)
Hot	23.9 (3.9)	23.8 (5.2)	23.1 (5.0)	22.0 (4.4)	20.7 (5.0)	18.9 (5.4)	18.7 (4.6)	18.4 (4.4)	21.2 (4.7)
Tense Arousal									
Control	11.9 (3.0)	11.3 (5.0)	10.7 (2.9)	11.8 (4.7)	11.7 (4.1)	11.9 (4.5)	11.0 (2.8)	11.3 (4.2)	11.5 (3.9)
Hot	11.9 (3.6)	12.6 (2.8)	11.7 (4.1)	12.0 (4.3)	12.8 (5.1)	14.8 (4.8)	13.4 (4.3)	14.8 (3.4)	13.0 (4.1)
Hedonic Tone									
Control	29.2 (2.9)	28.6 (4.6)	29.5 (3.0)	28.7 (3.9)	28.9 (3.5)	27.9 (4.9)	29.3 (3.0)	29.2 (3.9)	28.9 (3.7)
Hot	29.6 (3.2)	29.4 (3.4)	29.5 (4.7)	29.1 (4.6)	28.2 (4.9)	26.0 (5.3)	27.9 (4.2)	25.1 (2.7)	28.1 (4.1)

continued

Table 7.7. Mean mood scores. Standard deviations are shown in parentheses

	Before Performance 1	After Performance 1	Before Performance 2	After Performance 2	Before Performance 3	After Performance 3	Before Performance 4	After Performance 4	Mean
Anger/Frustration									
Control	5.7 (0.8)	5.7 (2.8)	5.4 (0.6)	6.1 (2.8)	5.7 (1.0)	5.7 (2.5)	5.4 (0.5)	5.7 (1.9)	5.7 (1.6)
Hot	5.7 (1.1)	5.7 (2.5)	6.1 (2.3)	6.1 (3.3)	6.1 (2.4)	7.0 (1.8)	7.0 (2.0)	7.5 (2.8)	6.4 (2.3)

Table 7.7 (continued). Mean mood scores. Standard deviations are shown in parentheses

Anger/Frustration was affected by the condition ($F = 11.22$, $df = 1, 10$, $p < 0.01$), the duration of the chamber exposure ($F = 3.37$, $df = 7, 77$, $p < 0.01$), and by an interaction between these two variables ($F = 2.64$, $df = 7, 77$, $p < 0.05$). Analysis of this interaction indicated a significant increase in Anger/Frustration towards the end of the experimental exposure. In the heat, the ratings recorded after the third and before the final performance measurement periods (the ratings were of identical value) were higher than those observed before and after the first measurement period ($p <0.05$ for both comparisons). The rating recorded on completion of the final performance measurement period was higher than those observed before and after the first measurement periods ($p < 0.01$ for both comparisons), before and after the second measurement periods, and before the third measurement period ($p < 0.05$ for all comparisons). No significant variation in ratings was evident during the control exposure. Comparison of the Anger/Frustration ratings between the control and experimental exposures revealed that ratings were higher in the heat after the third performance measurement period ($p < 0.05$), and before and after the final measurement period ($p < 0.01$ for both comparisons).

Thermal Comfort

The mean ratings of thermal comfort in the control and experimental sessions are shown in Table 7.8. These indicate that the participants were uncomfortably warm during the experimental exposure, and that discomfort tended to increase with the duration of the exposure to heat.

	Control Session	Experimental Session
Baseline	0.1 (0.3)	0 (0.4)
Before First Performance Session	0.1 (0.5)	1.5 (0.5)
After First Performance Session	0 (0.6)	1.7 (0.7)
Before Second Performance Session	0 (0.6)	1.9 (0.7)
After Second Performance Session	0 (0.6)	1.9 (0.7)
Before Third Performance Session	0 (0.5)	2.2 (0.7)
After Third Performance Session	0.2 (0.7)	2.3 (0.6)
Before Fourth Performance Session	0.1 (0.4)	2.4 (0.6)
After Fourth Performance Session	0.1 (0.4)	2.4 (0.7)
Mean During Chamber Exposure	0.1 (0.5)	2.0 (0.7)

Table 7.8. Mean thermal comfort ratings (a rating of 0 indicates comfort). Standard deviations are shown in parentheses

The Effects of the Experimental Exposure on Thermal Physiological and Psychological State: Summary

The participants experienced substantial thermal strain during the experimental exposure. Rectal and skin temperatures, heart rate, and sweat secretion were significantly higher in the hot condition. This thermal strain was accompanied by an increase in subjective discomfort. The intensity of thermal strain increased over the course of the exposure to heat. Individual variation in the core temperature response to heat was also evident (see Figure 7.3).

The mean values of rectal temperature during performance measurement in the control exposure were similar to those observed in the control immersions in the previous experiments. However, the mean values of rectal temperature during the thermally stressful exposure were lower than those recorded in the experimental immersions in the previous studies. During the first two performance measurement periods in the hot exposure, mean rectal temperature was more than one degree Celsius lower than the values recorded during the experimental immersions. The mean values of rectal temperature during the third and final performance assessment periods were comparable with but slightly lower than those observed in the immersion experiments.

Cortisol secretion increased with the duration of thermal strain. The effects of heat strain on mood were similar to those observed in the immersion experiments. Tense Arousal and Anger/Frustration were higher in the experimental exposure. Subjective arousal and Hedonic Tone ratings tended to be lower in the heat. Mood varied with the duration of thermal strain: Tense Arousal and Anger/Frustration increased, and Energetic Arousal and Hedonic Tone decreased over the course of the hot exposure.

Psychological Performance Data

The performance data were analysed using repeated-measures analysis of covariance, with baseline performance treated as a covariate. The independent variables included in the analysis were the condition, the duration of the exposure, the order in which the performance tasks were completed, and the order of exposure to the two conditions. Task variables were included as appropriate. Where necessary, the performance data were transformed to meet the assumptions of parametric analysis.

Significant effects were analysed further using the Newman-Keuls range test and Bonferroni *t* test.

As in the previous experiments, only those findings that are pertinent to the focus of the experiment are described below. Psychological performance was affected by several of the independent variables, but only the main effects of thermal strain and the interactions of thermal strain with other variables are described. The means reported have been adjusted on the basis of baseline performance, and where applicable, have been back-transformed and adjusted for bias. The mean values of the performance variables are shown in Appendix IV.

The Effects of Thermal Strain on Performance

The general increase in the speed of performance during thermal strain observed in the immersion experiments was reproduced in this study. Faster performance in the heat was evident in several of the performance measures. Shorter reaction times during thermal strain were observed in the second presentation of the variable foreperiod simple reaction task ($F = 8.22$, $df = 1, 9$, $p < 0.05$; see Figure 7.4) and the verbal reasoning task ($F = 5.96$, $df = 1, 8$, $p < 0.05$; see Figure 7.5). Thermal strain reduced overall reaction times in the focused attention task ($F = 10.32$, $df = 1, 7$, $p < 0.05$; see Figure 7.6) and the categoric search task ($F = 14.16$, $df = 1, 7$, $p < 0.01$; see Figure 7.7). In the vigilance task, reaction time to signals was lower in the heat ($F = 8.35$, $df = 1, 6$, $p < 0.05$; see Figure 7.8). The magnitude of the reduction in reaction time in these tasks ranged from three to ten percent. The decrease in reaction time in the verbal reasoning task was mirrored in an increase in the number of trials completed during thermal strain ($F = 7.39$, $df = 1, 8$, $p < 0.05$; the mean values were 48 and 55 trials in the control and experimental exposures, respectively).

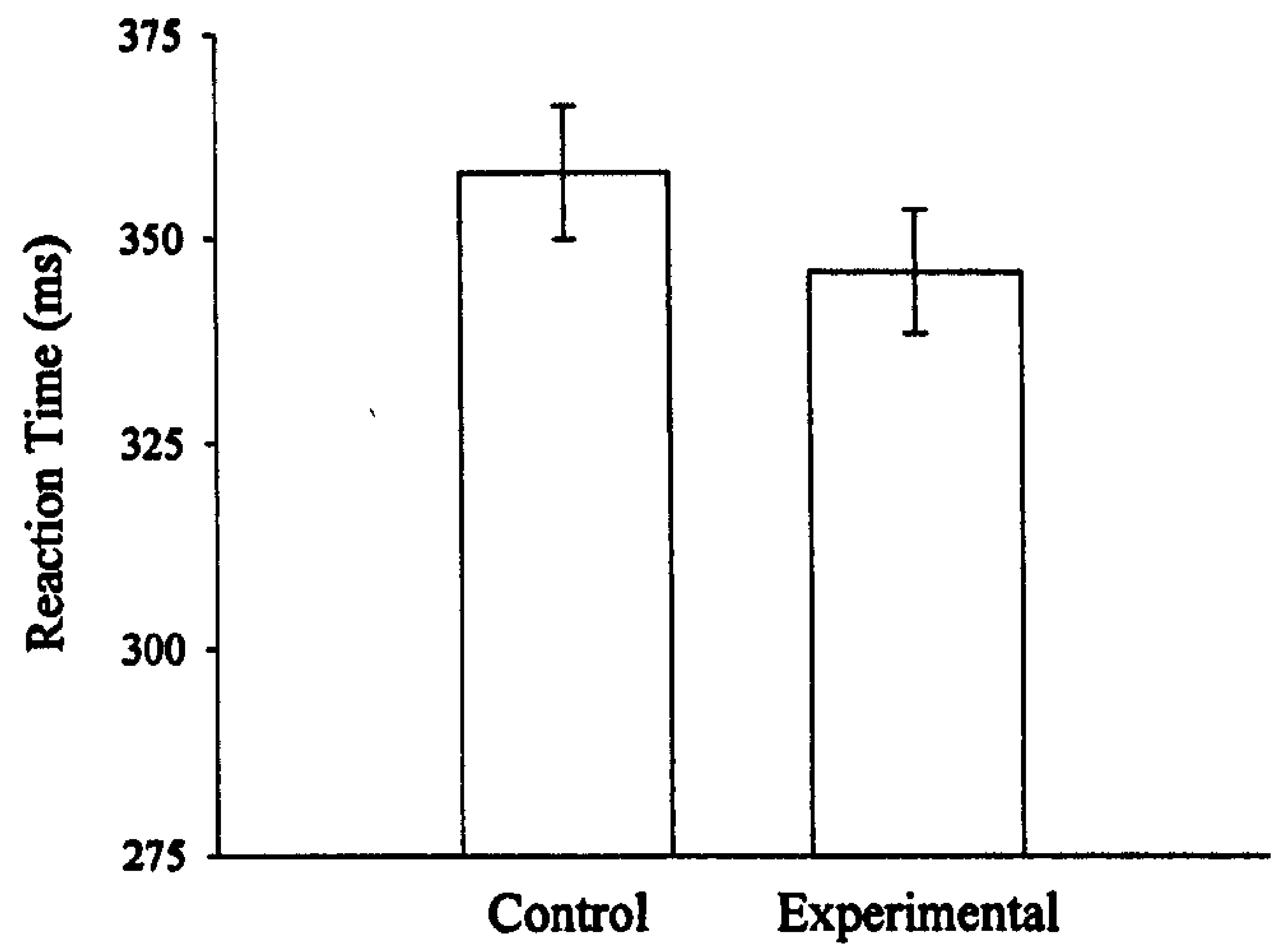

Figure 7.4. Variable foreperiod simple reaction task (second presentation): Mean reaction time in the control and experimental exposures. Standard errors of the mean are shown (95% confidence intervals)

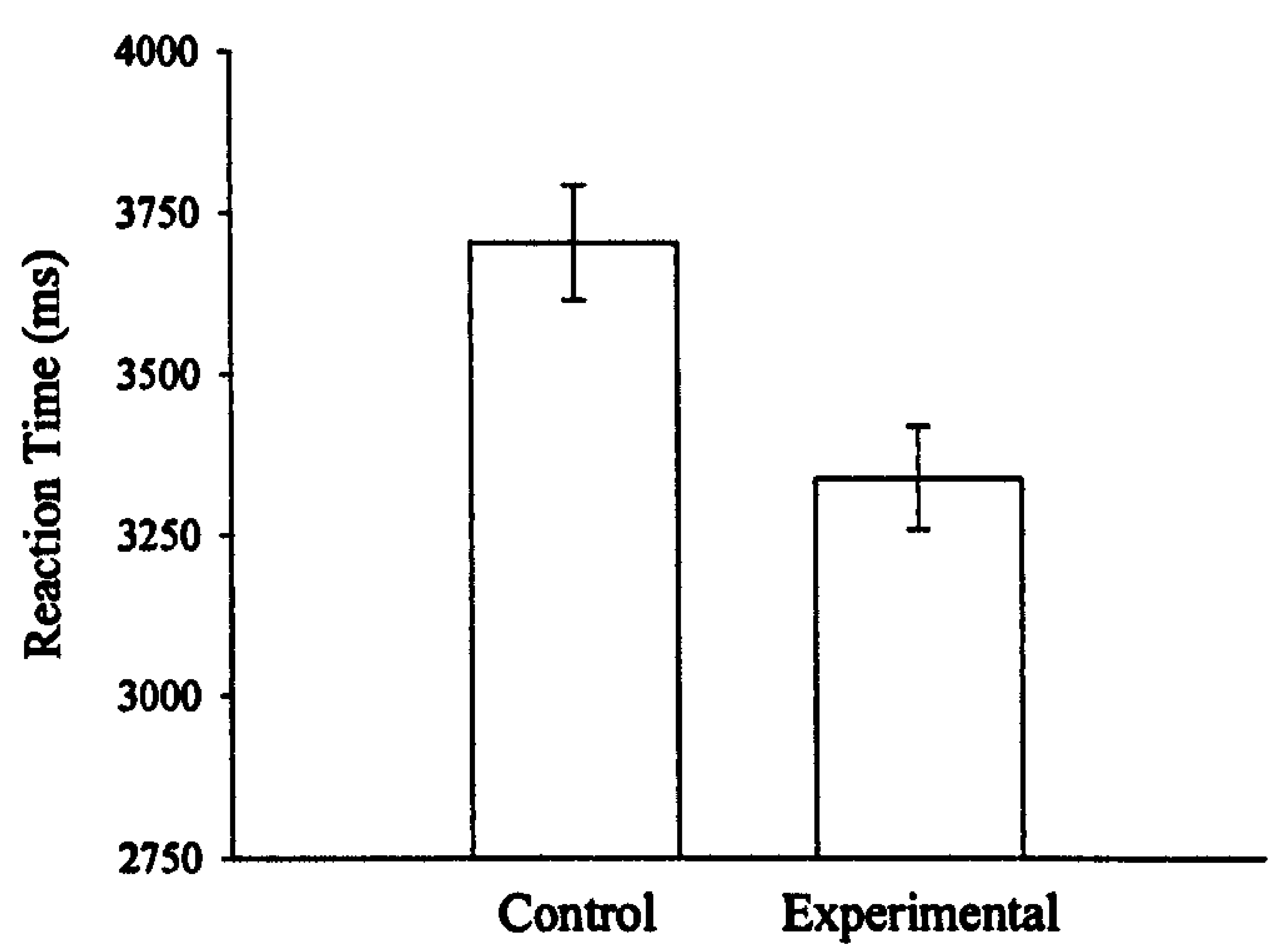

Figure 7.5. Verbal reasoning task: Mean reaction time in the control and experimental exposures. Standard errors of the mean are shown (95% confidence intervals)

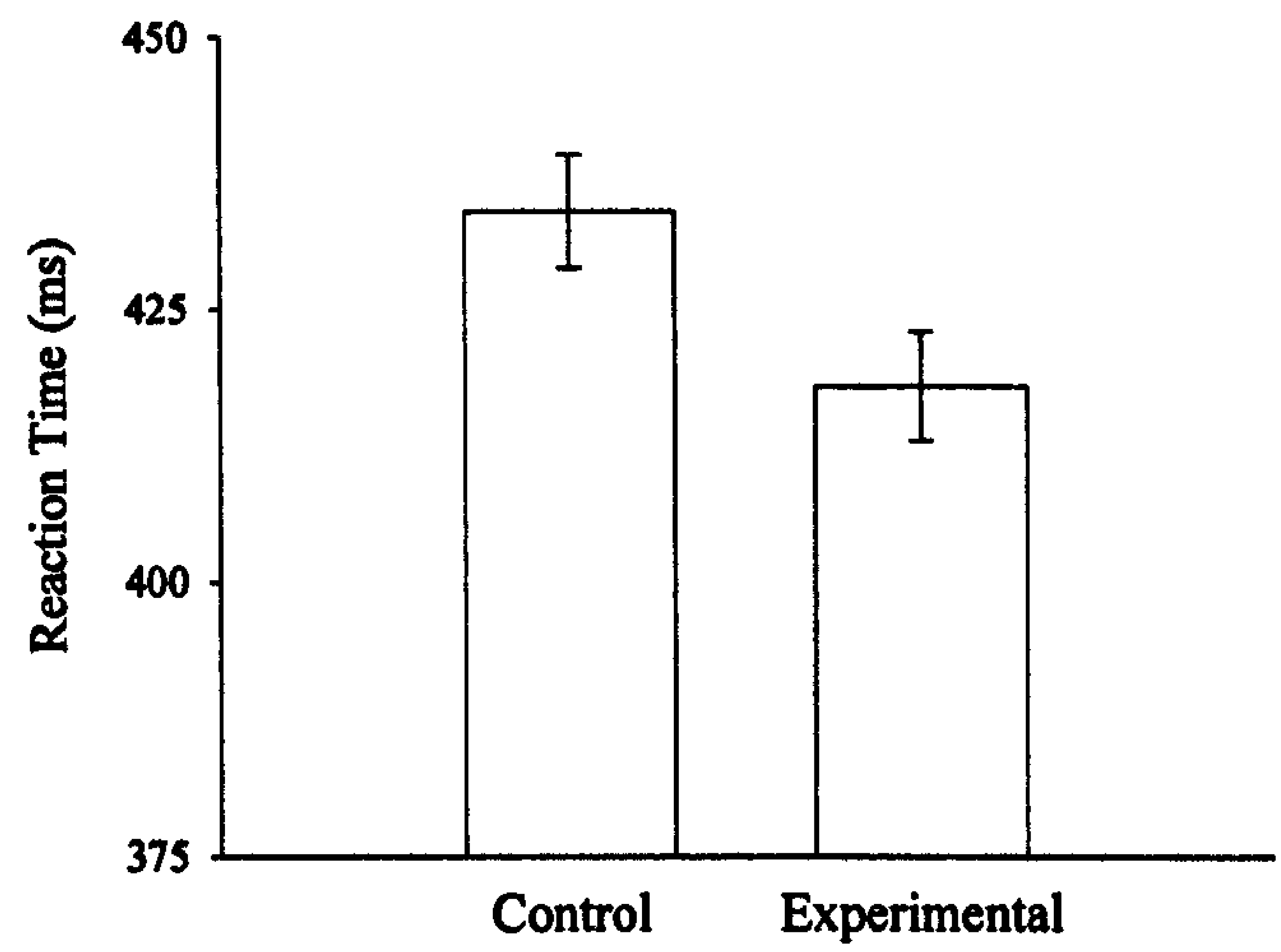

Figure 7.6. Focused attention task: Mean overall reaction time in the control and experimental exposures. Standard errors of the mean are shown (95% confidence intervals)

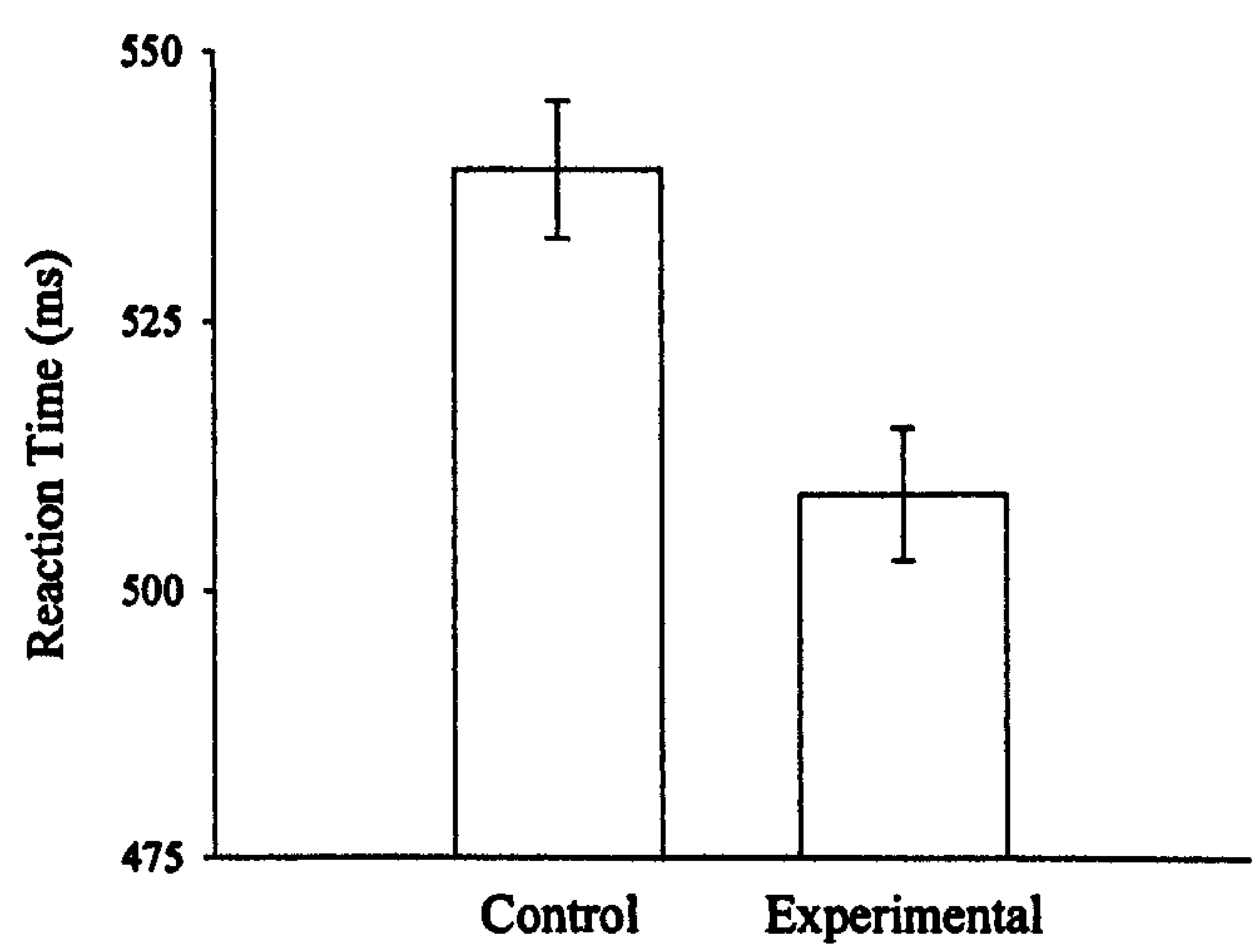

Figure 7.7. Categoric search task: Mean overall reaction time in the control and experimental exposures. Standard errors of the mean are shown (95% confidence intervals)

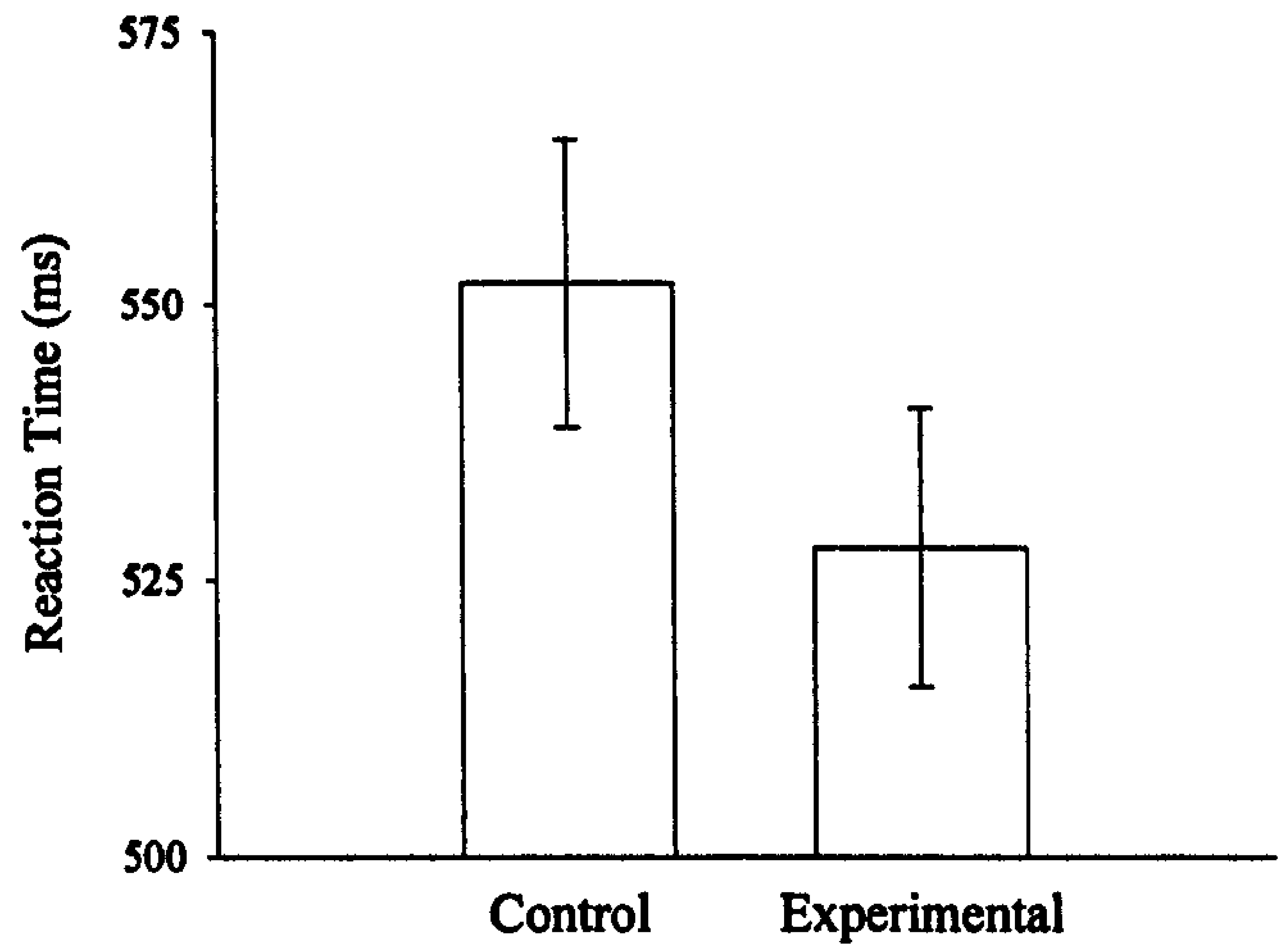

Figure 7.8. Vigilance task: Mean reaction time to signals in the control and experimental exposures. Standard errors of the mean are shown (95% confidence intervals)

No significant effects of thermal strain on reaction time were evident in the fixed foreperiod simple reaction task, the first presentation of the variable foreperiod simple reaction task, and the recognition memory task. Scrutiny of the mean reaction times in these tasks indicated that performance on the variable foreperiod reaction task and the recognition memory task tended to be faster in the heat, but no trend in the fixed foreperiod reaction task was discernible (see Table 7.9).

	Control Exposure	Experimental Exposure
Simple Reaction Task (fixed foreperiod)	279 (83)	280 (76)
Simple Reaction Task (variable foreperiod) First presentation	327 (77)	318 (61)
Recognition Memory Task	922 (171)	914 (157)

Table 7.9. Mean reaction times (ms) in the fixed foreperiod simple reaction, variable foreperiod simple reaction, and recognition memory tasks. Standard deviations are shown in parentheses

In the immersion experiments, there was no evidence that the faster performance observed during thermal strain was associated with a reduction in accuracy. In the present experiment, a deterioration in accuracy in the recognition memory task during heat strain was observed ($F = 5.97$, $df = 1, 9$, $p < 0.05$; see Table 7.10). In the remaining tasks, accuracy did not vary significantly with thermal strain. Mean accuracy scores are shown in Table 7.10.

In the vigilance task, signal detection rate was higher during thermal strain ($F = 20.14$, $df = 1, 8$, $p < 0.01$). The mean detection rates in the control and experimental conditions were 4.3 and 4.8 signals per minute, respectively. The false detection rate did not vary significantly between the control and experimental exposures (the mean values were 4.4 and 4.0 false detections per minute, respectively). These findings are consistent with those obtained when the task was administered in the first immersion experiment. The pattern of results suggests that the enhancement of signal detection rate in the heat was due to an increase in stimulus detectability rather than a reduction in the decision criterion.

	Control Exposure	Experimental Exposure
Focused Attention Task	96 (2)	96 (2)
Categoric Search Task	97 (3)	97 (3)
Verbal Reasoning Task	91 (10)	91 (10)
Recognition Memory Task	68 (12)	66 (13)

Table 7.10. Mean accuracy scores (% correct) in the selective attention, verbal reasoning, and recognition memory tasks. Standard deviations are shown in parentheses

In the immediate recall task, neither the number of words recalled nor the percentage of the words recalled that were correct was affected by thermal strain. The absence of variation in immediate recall with heat strain is consistent with the findings of the second immersion experiment.

A number of the variables derived from the selective attention tasks varied with thermal strain. However, consistent with the results of the first immersion experiment, there was little evidence that attention *per se* was affected by heat strain; the effects observed appear to reflect the general increase in performance speed during thermal strain. In the focused attention task, thermal strain reduced reaction time to trials in which the target letter was repeated from the previous trial ($F = 10.30$, $df = 1, 8$, $p < 0.05$; the mean values were 424 and 407 ms in the control and experimental conditions, respectively). Reaction time to trials in which the target differed from that in the preceding trial was also shorter in the heat ($F = 9.49$, $df = 1, 8$, $p < 0.05$; means were 451 and 437 ms in the control and experimental conditions, respectively). Similar effects were evident in the categoric search task. Reaction time to trials in which the target letter was repeated from the previous trial was lower during thermal strain ($F = 11.59$, $df = 1, 7$, $p < 0.05$; means were 527 and 504 ms in the control and experimental exposures, respectively). The mean reaction time to trials in which the target differed from that in the previous trial was shorter in the heat ($F = 20.15$, $df = 1, 9$, $p < 0.01$; means were 554 and 526 ms in the control and experimental conditions, respectively).

The Effects of the Duration of Thermal Strain on Performance

Performance was largely unaffected by the duration of thermal strain. Main effects of the duration of exposure were observed in a number of the measures, but there was little evidence that the impact of the duration of exposure varied between the control and experimental sessions. No two-way interactions between the condition and the duration of the exposure were found. Three three-way interactions involving the condition and the duration of exposure are described below, but given the relatively small sample tested, these effects are unlikely to be robust.

In the second presentation of the variable foreperiod simple reaction task, reaction time was affected by an interaction of the condition, the duration of the exposure, and time on task ($F = 2.67$, $df = 6, 60$, $p < 0.05$; means are shown in Table 7.11). Analysis of this effect revealed variation in performance with time on task in the third performance measurement period in the heat; longer reaction times were observed in the final minute than in either the first or second minute of the task ($p < 0.05$ for both comparisons). In addition, reaction time in the final minute of the final performance assessment conducted in the heat was lower than that observed during the equivalent period in the control exposure ($p < 0.05$), and those recorded in the final minute of the first and second assessments in the heat ($p < 0.05$ for both comparisons), and the third assessment in the heat ($p < 0.01$).

	Control Exposure			Experimental Exposure		
	First Minute	Second Minute	Third Minute	First Minute	Second Minute	Third Minute
First Performance Assessment	360 (76)	358 (146)	348 (70)	322 (42)	361 (49)	351 (70)
Second Performance Assessment	347 (62)	373 (68)	387 (102)	350 (99)	357 (71)	361 (121)
Third Performance Assessment	349 (80)	348 (99)	361 (85)	323 (93)	334 (106)	381 (113)
Fourth Performance Assessment	343 (94)	349 (74)	376 (129)	321 (79)	363 (143)	313 (43)

Table 7.11. Variable foreperiod simple reaction task (second presentation): Mean reaction times (ms) for condition, duration of exposure, and time on task. Standard deviations are shown in parentheses

In the vigilance task, an interaction of the condition, the duration of the exposure, and the order in which the performance tasks were completed affected both the reaction time to signals ($F = 5.22$, $df = 3, 21$, $p < 0.01$) and the false alarm rate ($F = 3.35$, $df = 3, 27$, $p < 0.05$). Analysis of the latter effect revealed no significant variation across means. Analysis of the reaction time data indicated that, during thermal strain, the mean reaction latency in the third performance assessment was lower than that in the final assessment when the tasks were completed in the 'standard' order (in which the vigilance task was the third measure) ($p < 0.05$; see Table 7.12). In addition, reaction time in the final performance assessment was significantly lower in the hot than in the control condition when the tasks were completed in the standard order ($p < 0.01$).

	Control Exposure		Experimental Exposure	
	Standard Task Order	Reverse Task Order	Standard Task Order	Reverse Task Order
First Performance Assessment	526 (40)	558 (86)	547 (64)	515 (72)
Second Performance Assessment	582 (70)	574 (122)	553 (52)	540 (114)
Third Performance Assessment	543 (47)	541 (72)	580 (106)	495 (56)
Fourth Performance Assessment	581 (89)	510 (63)	494 (67)	504 (96)

Table 7.12. Vigilance task: Mean reaction times to signals (ms) for condition, duration of exposure, and task order. Standard deviations are shown in parentheses

The Effects of Task Variables on Performance during Thermal Strain

In both immersion experiments, reaction time in the verbal reasoning task was affected by an interaction between the condition and the syntactic complexity of the stimuli. In the present experiment, reaction time varied with the syntactic complexity of the stimuli ($F = 6.78$, $df = 3, 26$, $p < 0.01$), but this effect did not interact with thermal strain.

The Effects of Time on Task on Performance during Thermal Strain

The data for each one-minute block of the simple reaction and vigilance tasks were analysed to assess the impact of time on task on performance. Performance in the fixed foreperiod simple reaction task and the first presentation of the variable foreperiod reaction task was unaffected by time on task. As noted above, an interaction of the condition, the duration of the exposure, and time on task was evident in the second presentation of the variable foreperiod simple reaction task ($F = 2.67$, $df = 6, 60$, $p < 0.05$; means are shown in Table 7.11). In the third performance testing period during thermal strain, reaction time in the final minute of the task was greater than that in either the first or second minute ($p < 0.05$ for both comparisons). The mean reaction time in the final minute of the final performance assessment in the heat was lower than that recorded in the equivalent period in the control condition ($p < 0.05$), and those observed in the final minute of the first and second assessments in the heat ($p < 0.05$ for both comparisons), and the third assessment in the heat ($p < 0.01$).

In the vigilance task, signal detection rate varied with time on task ($F = 9.96$, df = 2, 19, $p < 0.01$). This effect interacted with the condition and the order in which the participants were exposed to the conditions ($F = 3.82$, df = 2, 17, $p < 0.05$). Further analysis indicated that this interaction reflected variation in the effect of time on task between the participants' first and second exposures, regardless of the condition.

The Perceived Impact of Thermal Stress on Psychological Performance

The mean rating of the perceived impact of heat on psychological performance was 3, indicating that, overall, the participants believed that heat impairs performance. Two participants gave ratings of 5 (i.e. performance slightly improved in the heat); the remaining participants rated the impact of heat on performance as negative.

The Performance of the Participants who withdrew from the Experimental Condition

The data for the two participants who withdrew from the experimental condition were excluded from inferential statistical analysis. However, as these individuals had been unable to tolerate the thermally stressful condition, it was of interest to identify any trends in their performance in the heat. The mean values of the principal performance variables for these participants are presented in Appendix V (the means have been adjusted on the basis of baseline performance).

In the selective attention, verbal reasoning, and recognition memory tasks, the performance of the individuals who withdrew was consistent with the performance of those who completed the experimental exposure. In the vigilance task, the effects of heat on the false detection rate and reaction time to signals were also similar across the two groups of participants. However, in the case of the participants who withdrew, a reduction in signal detection rate in the heat was evident; this contrasts with the enhancement of signal detection demonstrated by those who completed the experimental exposure.

The participants who withdrew tended to perform poorly in the heat in the immediate recall task (both the number of words recalled and the accuracy of recall deteriorated) whereas the immediate recall of those who completed the exposure was unaffected by thermal strain. In addition, those who withdrew tended to show longer simple reaction times in the heat.

Covariation between Mood and Psychological Performance during Thermal Strain

To identify any association between mood and psychological performance in the heat the covariation between the mood and performance data was examined. Only those variables that had been significantly affected by heat were included in the analysis. Correlation coefficients between the change in the performance and mood variables from baseline to each of the performance testing periods in the control and experimental exposures (i.e. baseline minus chamber values) were calculated (see Appendix VI). Ten percent of these coefficients were statistically significant at a probability of five percent or less (using a two-tailed test).

Examination of the significant coefficients indicated little consistent covariation between mood and performance in the heat. There was rather limited evidence of a positive association between Anger/Frustration scores and reaction time in the verbal reasoning, vigilance, and categoric search tasks during thermal strain. However, this pattern of association appears spurious, as it contradicts the decrease in reaction time and the increase in Anger/Frustration observed in the heat. No obvious patterns of covariation between performance and Energetic Arousal, Tense Arousal, and Hedonic Tone were evident.

Covariation between the Physiological Variables and Performance in the Experimental Condition

To identify any association between physiological response and psychological performance in the heat the correlation coefficients between the change in the physiological and performance variables from baseline to each of the performance testing periods in the control and experimental conditions were examined (see Appendix VI). Ten percent of these coefficients were statistically significant at a probability of five percent or less (two-tailed test).

Scrutiny of the significant correlation coefficients yielded some evidence that, during exposure to heat, core temperature was positively associated with the speed of performance in the selective attention, verbal reasoning, and variable foreperiod simple reaction tasks. There was also some limited evidence of a positive association between heart rate and performance speed in the heat. No consistent patterns of covariation between performance in the heat and either skin temperature or cortisol secretion were observed.

Discussion

The principal aim of this experiment was to assess the extent to which the changes in performance observed in the water immersion experiments would generalize to conditions involving exposure to a more realistic thermal stress. In addition, the experiment sought to investigate the impact of prolonged heat strain on performance.

The participants experienced marked thermal strain during the experimental exposure. Core and skin temperatures, heart rate, and sweat secretion were significantly elevated in the heat, and thermal discomfort was increased. Two participants withdrew from the experimental condition because of intolerable discomfort. The mean values of core temperature during performance measurement in the experimental exposure were lower than those recorded in the experimental immersions in the previous studies. During the first and second performance measurement periods, rectal temperature was more than one degree Celsius lower than the values observed during hot water immersion. During the third and the final performance assessment periods, the values of rectal temperature were closer to but still lower than those during immersion.

Body temperatures and heart rate varied over the course of the experimental exposure; thermal strain intensified with the duration of the exposure to heat. Individual differences in the core temperature response to heat stress were also evident. This temporal and individual variation in core temperature illustrates the rationale for the precise control of body temperature sought in the immersion experiments.

The pattern of variation in mood with thermal strain was similar to that observed in the immersion experiments. Tense Arousal and Anger/Frustration scores were elevated during thermal strain. Energetic Arousal and Hedonic Tone tended to be lower during heat strain. Mood varied over the course of the thermally stressful exposure; Tense Arousal and Anger/Frustration increased, and Energetic Arousal and Hedonic Tone decreased. Cortisol secretion increased with the duration of the experimental exposure.

The general decrease in reaction time during thermal strain evident in the immersion experiments was largely replicated in the climatic chamber. Reaction time in the second presentation of the variable foreperiod simple reaction task and overall reaction times in the selective attention and verbal reasoning tasks were significantly lower during heat strain. Reaction time to signals in the vigilance task was also significantly reduced. Reaction latencies in the recognition memory task and the first presentation of the variable foreperiod reaction task tended to be shorter in the experimental exposure, but this variation was not significant.

In the fixed foreperiod simple reaction task, no difference in mean reaction time between the control and experimental conditions was discernible. This contrasts with the general decrease in reaction time evident during thermal strain. A significant reduction in reaction time in this task was observed in both immersion experiments, but these effects were relatively small ($p < 0.05$ in both experiments). The absence of an effect in the climatic chamber suggests that the impact of thermal strain on the performance of this task was not robust and was detectable only during the precisely controlled heat strain induced in the immersion experiments.

The immersion experiments yielded no evidence that the general decrease in reaction time during thermal strain reflected a trade-off between the speed and accuracy of performance. Similarly, in this experiment, accuracy was largely unaffected by heat strain. However, a significant deterioration in accuracy in the recognition memory task was observed during the experimental exposure (accompanied by a non-significant reduction in reaction time). This finding is inconsistent with the observation in the second immersion experiment that recognition memory accuracy was unaffected by thermal strain (a non-significant reduction in reaction time was also evident in that experiment). The deterioration in accuracy was relatively small; mean accuracy scores were 68% (s.d. = 12) and 66% (s.d. = 13) in the control and experimental exposures, respectively ($p < 0.05$). This suggests that the effect may not be robust. Furthermore, no other indications of deterioration in performance accuracy in the heat were evident.

The effects of thermal strain observed in the cognitive vigilance task administered in the first immersion experiment were replicated in the climatic chamber. Signal detection rate was higher during heat strain. The false detection rate did not vary significantly with thermal strain, which indicates that the enhancement of signal detection rate reflects an increase in signal detectability rather than a reduction in the decision criterion.

Consistent with the results of the first immersion experiment, selective attention was unaffected by thermal strain. A number of the variables derived from the focused attention and categoric search tasks varied with heat strain, but the effects observed simply reflect the general decrease in reaction time associated with elevation of body temperature. None of the attentional phenomena measured by the tasks (e.g. the Eriksen effect; the place repetition effect) was affected by heat strain.

Performance in the immediate recall task was unaffected by thermal strain, which mirrors the findings of the second immersion experiment.

The consistency of the findings of the immersion and climatic chamber experiments indicates that the performance effects measured during precisely controlled thermal strain generalize to conditions involving exposure to a more realistic thermal stress. However, the results of the immersion experiments and those of the ecologically more valid climatic chamber experiment are incompatible with the perceived effects of occupational exposure to thermal stress measured in the field. The Royal Air Force personnel surveyed during overseas deployments reported that heat stress impaired sustained concentration, fine motor control, and strenuous activity. None of the respondents reported that performance improved in the heat. The discrepancies between the perceived effects of thermal stress and those measured in the laboratory may simply reflect the unreliability of subjective assessments of the impact of stressors on psychological performance (e.g. Poulton, 1977; Yesavage and Leirer, 1986). Indeed, in the climatic chamber experiment, eighty-five percent of the participants reported that their performance deteriorated in the experimental exposure. Moreover, it is possible that the psychological effects reported in the questionnaire study were influenced by extraneous variables associated with deployment overseas.

The performance during thermal strain of the two participants who withdrew from the experimental condition was broadly consistent with that of those who completed the exposure. However, some differences between the two groups were evident. The individuals who withdrew tended to detect fewer signals in the vigilance task during exposure to thermal stress. In addition, their performance in the simple reaction and immediate recall tasks tended to deteriorate in the heat. These findings must be interpreted cautiously, but they suggest that the impact of heat on some aspects of performance may be affected by individual differences in tolerance of the discomfort associated with thermal strain.

An important aim of this experiment was to examine the effects of prolonged thermal strain on performance. However, in spite of the substantial duration of the exposure, little evidence of variation in performance was observed. No two-way interactions between the condition and the duration of the exposure were evident. In the second presentation of the variable foreperiod simple reaction task, performance was affected by an interaction between the duration of thermal strain and time on task. Reaction time to signals in the vigilance task was affected by an interaction between the duration of heat strain and the order in which the performance tasks were completed. Further analysis of these interactions yielded unremarkable patterns of results. Moreover, in light of the relatively small sample tested, these effects are unlikely to be robust.

Previous research on performance during thermal stress has typically utilized heat exposures of two or three hours duration. There is a dearth of data in the literature on the effects of extended exposure to heat stress. Fine et al (1960) administered an anagram task to volunteers during the first and the penultimate thirty-minute periods of a six-hour exposure to thermal stress. In the first thirty minutes of the exposure, fewer anagrams were correctly solved in the heat. Performance during the penultimate thirty-minute period did not vary with heat stress. Fine and Kobrick (1978) measured soldiers' performance on several message reception and decoding tasks during a seven-hour exposure to heat stress. Error rates were higher during thermal stress, and tended to increase with the duration of the exposure to heat.

The limited evidence of variation in performance with the duration of thermal strain found in this experiment is somewhat surprising. On the assumption that an increase in nerve conduction velocity underlies the shorter reaction times observed during thermal strain, and given that heat strain intensified over the course of the experimental exposure, it might be expected that reaction time would decrease as the duration of the exposure increased. Scrutiny of mean reaction times in the control and experimental exposures indicated that reaction time in the verbal reasoning, categoric search, and recognition memory tasks did indeed tend to decrease with increased duration of thermal strain. However, this pattern was not evident in all of the performance tasks. It is possible that the marked individual variation in physiological response to the experimental exposure may have obscured any specifically duration-related effects of heat strain on performance. Scrutiny of the correlation coefficients between the physiological and performance variables yielded some evidence that core temperature was positively related to the speed of performance in the selective attention, verbal reasoning, and variable foreperiod simple reaction tasks. This indicates that variation in performance is associated with temporal *and* individual variation in body temperature, and lends support to the proposal that individual differences in physiological response may have clouded any duration-related changes in performance.

The results of this experiment do not support theoretical accounts of performance during thermal stress proposed by previous researchers. The findings are incompatible with a classic arousal theory account of the relationship between heat and performance. Energetic Arousal decreased and Tense Arousal increased during the experimental exposure. However, as in the first immersion experiment, there was little evidence of consistent covariation between mood and performance during thermal strain.

The results of this study are also inconsistent with Allnutt and Allan's proposal that elevation of core temperature enhances performance speed whereas elevation of skin temperature impairs accuracy (Allnutt and Allan, 1973). The speed of performance was enhanced during thermal strain, but with the exception of a deterioration in the accuracy of recognition memory, performance accuracy was unaffected, in spite of the marked increase in skin temperature.

Conclusions

The results of this experiment indicate that the performance effects observed during precisely controlled thermal strain in the immersion experiments generalize to conditions involving exposure to an ecologically more valid source of heat strain. The general decrease in reaction time evident during thermal strain in the immersion experiments was replicated in the climatic chamber. The enhancement of signal detection in the cognitive vigilance task found in the first experiment was also reproduced. Consistent with the results of the immersion experiments, no significant effects of thermal strain on selective attention and immediate recall were observed.

There were some minor inconsistencies between the effects of thermal strain on performance observed in the immersion experiments and those measured in the climatic chamber. The absence of variation in performance accuracy with thermal strain in the immersion studies was largely replicated. However, the accuracy of recognition memory deteriorated during heat strain in the climatic chamber. This effect was small, and may not be robust. In both immersion experiments, reaction time in the fixed foreperiod simple reaction task was significantly shorter during heat strain. However, in the chamber experiment, performance in this task did not vary with thermal strain, and no trends in the data were discernible. This suggests that the effect of thermal strain on the performance of this task is rather weak and is observable only during precisely controlled elevation of body temperature.

In spite of the greater ecological validity of the climatic chamber experiment, there were clear discrepancies between the perceived effects of occupational exposure to thermal stress measured in the field and those observed in the climatic chamber. These differences appear largely to reflect the limited validity of subjective measures of psychological performance, as evidenced by the inconsistency between the perceived and objective changes in performance measured in the climatic chamber.

Although the participants were exposed to thermal stress for an extended period, there was little evidence that performance varied with the duration of thermal strain. It is possible that individual variation in the physiological response to the heat stress may have obscured any duration-related effects of heat strain on performance.

The effects of thermal strain observed in this experiment are inconsistent with theoretical accounts of psychological performance in the heat proposed by previous researchers. Contrary to arousal theory, there was little evidence of consistent co-variation between subjective arousal and performance. The results of the experiment do not support the proposal that elevation of skin temperature impairs the accuracy of psychological performance.

CHAPTER 8

General Discussion

The physiological and psychological effects of thermal stress have important implications for the control of occupational exposure to heat. The impact of thermal stress on physical health is unequivocal. This research programme has demonstrated that thermal stress also compromises psychological well being. In both the laboratory and the field, heat had a negative impact on mood, reducing alertness and ratings of hedonic tone, and increasing tension and irritability. Cortisol secretion increased during prolonged exposure to heat stress. The climatic chamber experiment and the survey of military personnel during overseas deployments revealed that the negative effects of thermal stress on psychological state were accompanied by a deterioration in self-assessed psychological performance. This confirmed anecdotal evidence that heat stress is widely perceived to impair mental function. However, this perception is not supported unequivocally by previous research on psychological performance in the heat, which has yielded a largely inconsistent pattern of findings. The general aim of this research programme was to elucidate the effects of thermal stress on cognitive and psychomotor function. The results indicate that the perceived impact of heat on psychological performance is almost entirely erroneous.

Much of previous research on psychological performance in the heat is beset by methodological shortcomings, including poor statistical power, and reliance on a limited range of performance measures of largely undemonstrated sensitivity. Most significantly, the majority of investigators have neglected the physiological impact of thermal stress. In this research programme, particular emphasis was placed on defining the independent variable in terms of physiological strain. The precise control of thermal strain achieved in the water immersion experiments allowed the identification of consistent and replicable effects of elevation of body temperature on performance. The results of the ecologically more valid climatic chamber experiment indicate that these effects are largely generalizable to conditions involving exposure to more realistic sources of thermal strain.

The Effects of Thermal Strain on Psychological Performance

The most salient effect of thermal strain on psychological performance was a general decrease in reaction time. Table 8.1 shows the magnitude of the reductions in reaction time observed in the immersion and chamber experiments. Shortening of reaction time was a consistent feature of performance during heat strain. The sole inconsistency in this pattern was the absence of variation in the fixed foreperiod simple reaction task in the climatic chamber experiment. Enhancement of the speed of performance was also evidenced by an increase in the number of trials completed in self-paced tasks such as the verbal reasoning and semantic processing tasks, and, in the second immersion experiment, an increase in the rate of finger tapping.

With the exception of a small (and possibly spurious) reduction in recognition memory accuracy in the climatic chamber experiment, the accuracy of performance was unaffected by heat strain.

The evidence that elevation of body temperature increases nerve conduction velocity and the speed of execution of motor responses (e.g. Buchtal and Rosenfalk, 1966; Stegeman and De Weerd, 1982; Goodman et al, 1984) provides a plausible explanation for the observed pattern of reduced reaction times without variation in accuracy. Previous research on the effects of thermal stress on reaction time has been of variable methodological quality and has produced a rather inconsistent body of findings. Several investigators have observed shorter reaction times during exposure to thermal stress (e.g. Pepler, 1959; Lovingood et al, 1967; Hygge, 1991), but Grether et al (1971), and Razmjou and Kjellberg (1992) reported that reaction time increased in the heat. The majority of previous studies have obtained negative results. The observation that a reduction in the motor stage of the reaction process during thermal strain was determined by elevation of arm temperature (Goodman et al, 1984) provides a tentative explanation for the absence of a consistent pattern of shorter reaction times in the literature. Previous research has typically exposed volunteers to elevated air temperatures, which may not necessarily cause significant elevation of limb temperatures, particularly if the thermal stress is relatively innocuous.

	First Immersion Experiment	Second Immersion Experiment	Climatic Chamber Experiment
Fixed foreperiod reaction task	3% ($p < 0.05$)	9% ($p < 0.05$)	0%
Variable foreperiod reaction task (1st presentation)	6% (n.s.)	8% ($p < 0.001$)	3% (n.s.)
Variable foreperiod reaction task (2nd presentation)	2% (n.s.)	not administered	3% ($p < 0.05$)
Four-choice reaction task	not administered	4% ($p < 0.01$)	not administered
Cognitive vigilance task	2% (n.s.)	not administered	4% ($p < 0.05$)
Visual vigilance task	not administered	6% ($p < 0.01$)	not administered
Verbal reasoning task	6% ($p < 0.05$)	8% (n.s.)	10% ($p < 0.05$)
Semantic processing task	6% ($p < 0.01$)	3% (not analysed)	not administered
Stroop task	4% ($p < 0.05$)	not administered	not administered
Focused attention task	5% (n.s.)	not administered	4% ($p < 0.05$)
Categoric search task	7% ($p < 0.05$)	not administered	6% ($p < 0.01$)
Recognition Memory Task	not administered	11% (n.s.)	1% (n.s.)

Table 8.1. Magnitude and statistical significance of reductions in reaction time during thermal strain in the water immersion and climatic chamber experiments

The results of a study by Preece, Iwi, Davies-Smith, Wesnes, Butler, Lim, and Varey (1999) on the effects of mobile telephone transmissions on psychological performance present an interesting parallel to the findings of this research programme. Preece and his colleagues observed that exposure to a simulated mobile phone signal shortened choice reaction time without affecting the accuracy of performance. The authors attributed this effect to an enhancement of synaptic transmission associated with superficial heating of the cerebral cortex caused by microwave radiation.

Table 8.1 reveals some variation across the three experiments in the magnitude of the reductions in reaction time during thermal strain. There are no consistent differences between the immersion and climatic chamber experiments in the magnitude of the effects observed, even though the mean value of core temperature during performance testing in the experimental immersions was approximately 0.6° C higher than that in the experimental exposure in the chamber experiment. The immersion and chamber experiments differed in several other significant respects, which may have had an impact on performance. Not least of these was the marked individual and temporal variation in body temperature in the climatic chamber. It would be valuable to conduct further research to quantify the relationship between thermal strain and performance change. One useful approach would be to measure performance while maintaining core temperature at each of several elevated values using the water immersion technique.

The second principal change in performance observed during thermal strain was an increase in signal detectability in the cognitive vigilance task administered in the first immersion experiment and the chamber experiment. This finding is inconsistent with the results of previous investigations of the effects of thermal stress on vigilance. In general, previous research has revealed that heat stress impairs signal detection, and has provided some evidence that this is attributable to a decrease in signal detectability. The novel pattern of results observed here may reflect the use of a cognitive vigilance task in contrast to the sensory tasks utilized in previous research. The substantial processing demand imposed by the task is also relevant to the effects observed; the relatively undemanding vigilance task administered in the second immersion experiment did not reveal any variation in signal detection or false detection rates with thermal strain.

In light of the evidence that elevation of body temperature increases nerve conduction velocity, it is conceivable that the improvement in signal detectability in the cognitive vigilance task has its origin in an increase in the speed of information processing during thermal strain. The magnitude of the improvement in processing capacity during thermal strain in the first immersion experiment was calculated as seven percent (see Chapter 4). In the climatic chamber experiment, the improvement in performance was of identical size. The similarity of the magnitude of this effect and of the decrease in reaction time during heat strain provides some support for the proposal that the improvement in signal detectability reflects an enhancement of the rate of information processing associated with an increase in neuronal conduction velocity.

The results of the experiments suggest that thermal strain does not alter selective attention. None of the attentional phenomena measured by the focused attention and categoric search tasks was affected by heat strain. The magnitude of the Stroop effect was also unaffected by thermal strain.

There was no evidence that short term or recognition memory was affected by thermal strain. These findings must be interpreted with caution, however, as it seems likely that the memory tasks used may have been insufficiently sensitive to detect changes in performance in the relatively small samples tested. The absence of variation in memory with heat strain is consistent with the findings reported by Holland et al (1985). However, this experiment, too, used a relatively small sample (twenty volunteers were tested).

One rather surprising finding in the second immersion experiment was that tracking was unaffected by thermal strain. This runs counter to the large majority of previous research, which indicates that psychomotor performance is impaired in the heat. On this basis, the absence of an effect must be considered questionable. Review of the literature suggests that task demand is an important determinant of tracking performance in the heat (Iampietro et al, 1969; Nunneley et al, 1979). The absence of variation in tracking performance in the second experiment may reflect a ceiling effect due to the relative ease of the task. Further research to examine more closely the impact of task variables on psychomotor performance during thermal strain would be useful.

The Effects of the Duration of Thermal Strain on Psychological Performance

An important aim of the second and third experiments was to address the impact of the duration of thermal strain on psychological performance. The limited evidence of variation in performance, particularly during the prolonged heat exposure in the climatic chamber experiment, was rather surprising. On the assumption that an increase in nerve conduction velocity underlies the changes in performance observed during thermal strain, and given that heat strain intensified with the duration of the experimental exposure in the climatic chamber, an improvement in performance over the course of the exposure might be predicted. It is possible that the marked individual variation in physiological response may have obscured any such duration-related effects of heat strain on performance. Alternatively, in light of the effects of heat on psychological state, a *deterioration* in performance over the course of the thermally stressful exposure could readily be accounted for in terms of a decline in motivation. Of course, if performance had changed over the course of the exposure, it would not have been possible to discern whether this variation was associated with the intensity or the duration of thermal strain, as these variables were confounded. For this reason, it would be valuable to examine the effects of prolonged, precisely controlled thermal strain on performance. Practical constraints limit the use of the water immersion technique to relatively short periods, and, therefore, it would be necessary to identify an alternative means of controlling body temperature. Wilkinson et al (1964) used an impermeable suit with forced air ventilation to maintain oral temperature at specific, elevated values for approximately two hours. In principle, a similar technique might allow precise control of body temperature over an extended period.

Theoretical Accounts of Performance during Thermal Strain

The increase in the speed of nerve conduction (and, presumably, other physiological processes) during elevation of body temperature provides a plausible explanation for the principal performance effects observed in this research programme. Few theoretical accounts of the relationship between thermal stress and performance have been proposed in the literature, and these are poorly elaborated. The lack of well-developed theory is frustrating. The results of this research provide further evidence that existing accounts of the effects of heat stress on performance are significantly flawed.

The most popular theoretical account of performance during thermal stress relies on classic arousal theory. However, the validity of arousal theory as an account of the relationship between heat stress and performance is unproven, primarily due to a lack of methodological rigour in the application of the theory in heat research. Arousal theory has invariably been used to describe rather than to predict the effects of thermal stress on performance. Investigators have typically inferred the impact of heat stress on arousal *post hoc* from the performance effects observed; collateral evidence of arousal change in the heat has rarely been obtained. If this approach were applied to account for the performance changes observed in this research programme, it would be concluded that arousal increased during thermal strain, as evidenced by the general decrease in reaction time and the improvement in signal detection rate in the cognitive vigilance task. This conclusion would be misleading; ratings of Tense Arousal increased during thermal strain, but Energetic Arousal was reduced. Moreover, there was little evidence of consistent covariation between either of these arousal variables and performance during thermal strain. The differential variation in these variables during heat strain illustrates that the concept of arousal as a unitary entity, which is implicit in arousal theory, is simplistic.

The results of this research programme do not support Allnutt and Allan's rather speculative proposal concerning the differential effects of core and skin temperatures on psychological performance (Allnutt and Allan, 1973). With the exception of the deterioration in recognition memory accuracy observed in the climatic chamber experiment, the accuracy of performance did not vary with thermal strain, in spite of the marked elevation of skin temperatures.

A number of investigators have examined explicitly the relationship between core body temperature and psychological performance in the heat. Several have reported that rectal temperature and performance are not associated (e.g. Mackworth, 1950; Pepler, 1958; Razmjou and Kjellberg, 1992). However, Wilkinson et al (1964) found that oral temperature was correlated with performance during thermal strain. There was limited evidence of a positive association between core temperature and the speed of performance in the first immersion experiment, but, of course, the variability of body temperature in this experiment was low. The climatic chamber experiment yielded more extensive but not universal evidence of co-variation between core temperature and reaction time. As noted above, further research to quantify the relationship between body temperature and performance change during thermal strain would be valuable.

Directions for Future Research

A number of avenues for investigation have been highlighted above, including quantification of the relationship between the intensity of thermal strain and performance change, and examination of the impact of prolonged but controlled heat strain on performance.

The implications of changes in psychological state associated with thermal strain merit attention. In both the laboratory and the field, exposure to heat stress produced marked negative changes in mood. There was some indication that these effects were associated with perceived deterioration of psychological performance, but there was little evidence that mood change was linked with objective variation in performance. However, there were some indications that the performance of the participants who withdrew from the thermally stressful climatic chamber exposure was impaired in the heat. This suggests that the impact of thermal stress on performance may be influenced by individual differences in tolerance of the discomfort associated with heat exposure.

Finally, from an applied perspective, the effects of thermal strain on psychological performance should not be studied in isolation from other environmental, state, and trait variables that affect cognitive and psychomotor function. The water immersion technique offers a means of controlling thermal strain precisely that could usefully be applied in combined stressor research.

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APPENDIX I

Experiment 1: Mean Values of the Performance Variables

Control Immersion	Experimental Immersion
303 (70)	293 (61)

Fixed Foreperiod Simple Reaction Task: Mean reaction time (ms)

Control Immersion	Experimental Immersion
343 (43)	323 (55)

Variable Foreperiod Simple Reaction Task (first presentation): Mean reaction time (ms)

Control Immersion	Experimental Immersion
374 (54)	365 (50)

Variable Foreperiod Simple Reaction Task (second presentation): Mean reaction time (ms)

Control Immersion	Experimental Immersion
Signal Detection Rate (signals detected/min)	
4.4 (1.6)	5.3 (1.7)
False Detection Rate (false detections /min)	
5.1 (2.1)	4.9 (1.7)
Reaction Time to Signals (ms)	
563 (102)	550 (85)

Vigilance Task

Control Immersion	Experimental Immersion
Reaction Time (ms)	
3336 (888)	3132 (830)
Number of Trials Completed	
56 (13)	61 (15)
Accuracy (percent correct)	
82 (19)	80 (18)

Verbal Reasoning Task

Control Immersion	Experimental Immersion
Reaction Time (ms)	
1483 (233)	1397 (268)
Number of Trials Completed	
116 (16)	126 (13)
Accuracy (percent correct)	
93 (4)	92 (4)

Semantic Processing Task

Control Immersion	Experimental Immersion
Overall Reaction Time (s)	
49 (7)	47 (8)
Overall Accuracy (percent correct)	
100 (0.5)	100 (0.3)
Magnitude of the Stroop Effect	
0.36 (0.15)	0.39 (0.14)

Stroop Task

Control Immersion	Experimental Immersion
Reaction Time (ms)	
479 (84)	456 (73)
Accuracy (percent correct)	
97 (5)	96 (5)

Focused Attention Task: Overall reaction time and accuracy

Control Immersion	Experimental Immersion
488 (78)	460 (73)

Focused Attention Task: Mean reaction time (ms) to trials in which the target letter differed to that in the previous trial

Control Immersion	Experimental Immersion
480 (93)	458 (74)

Focused Attention Task: Mean reaction time (ms) to trials in which the target letter was repeated from the previous trial

Control Immersion	Experimental Immersion
8 (34)	3 (24)

Focused Attention Task: Difference between mean reaction times (ms) to trials in which the target letter differed to that in the previous trial and trials in which the target letter was repeated from the previous trial

Control Immersion	Experimental Immersion
-9 (51)	27 (49)

Focused Attention Task: The Eriksen effect (ms)

Control Immersion	Experimental Immersion
Reaction Time (ms)	
596 (94)	556 (71)
Accuracy (percent correct)	
97 (2)	97 (3)

Categoric Search Task: Overall reaction time and accuracy

Control Immersion	Experimental Immersion
617 (89)	562 (75)

Categoric Search Task: Mean reaction time (ms) to trials in which the target letter differed to that in the previous trial

Control Immersion	Experimental Immersion
591 (100)	557 (70)

Categoric Search Task: Mean reaction time (ms) to trials in which the target letter was repeated from the previous trial

Control Immersion	Experimental Immersion
26 (42)	6 (33)

Categoric Search Task: Difference between mean reaction times (ms) to trials in which the target letter differed to that in the previous trial and trials in which the target letter was repeated from the previous trial

Control Immersion	Experimental Immersion
8 (6)	15 (12)

Categoric Search Task: Difference between mean reaction times (ms) to trials in which the laterality of the target was compatible or incompatible with the laterality of the required response

Control Immersion	Experimental Immersion
21 (28)	11 (30)

Categoric Search Task: The place repetition effect. Difference between mean reaction times (ms) to trials in which the target appeared in a different location to or the same location as that in the previous trial

Control Immersion	Experimental Immersion
61 (61)	28 (43)

Selective Attention Tasks: SPUL ('spatial uncertainty little'). Difference between mean reaction times (ms) to trials in the Categoric Search task in which the warning crosses were presented close together, the laterality of the target and the required response were compatible, and no distractor was presented, and to trials in the Focused Attention task in which the warning crosses were presented close to the target location, and no distractors were presented

APPENDIX II

Experiment 2: Mean Values of the Performance Variables

	Control Immersion		Experimental Immersion	
	a.m.	p.m.	a.m.	p.m.
First Measurement Period	300 (43)	274 (47)	274 (38)	251 (29)
Second Measurement Period	324 (66)	272 (46)	285 (31)	260 (41)
Overall Mean	293 (51)		268 (35)	

Fixed Foreperiod Simple Reaction Task: Mean reaction time (ms)

	Control Immersion		Experimental Immersion	
	a.m.	p.m.	a.m.	p.m.
First Measurement Period	353 (36)	326 (40)	314 (33)	312 (45)
Second Measurement Period	349 (53)	349 (35)	331 (35)	301 (30)
Overall Mean	344 (41)		315 (36)	

Variable Foreperiod Simple Reaction Task: Mean reaction time (ms)

	Control Immersion		Experimental Immersion	
	a.m.	p.m.	a.m.	p.m.
Reaction Time for Correct Responses (ms)				
First Measurement Period	559 (71)	523 (63)	530 (64)	506 (53)
Second Measurement Period	562 (80)	518 (41)	525 (54)	512 (79)
Overall Mean	541 (64)		518 (63)	
Accuracy (percent correct)				
First Measurement Period	99 (2)	99 (3)	99 (3)	99 (3)
Second Measurement Period	99 (3)	99 (2)	99 (2)	99 (3)
Overall Mean	99 (3)		99 (3)	

Choice Reaction Task

	Control Immersion		Experimental Immersion	
	a.m.	p.m.	a.m.	p.m.
First Measurement Period	328 (42)	340 (29)	349 (28)	349 (33)
Second Measurement Period	343 (35)	348 (32)	351 (34)	351 (38)
Overall Mean	340 (35)		350 (33)	

Tapping Task: Mean tapping rate (taps/min)

	Control Immersion		Experimental Immersion	
	a.m.	p.m.	a.m.	p.m.
Total Number of Words Recalled				
First Measurement Period	7.1 (2.5)	8.0 (1.4)	9.1 (1.2)	8.3 (1.9)
Second Measurement Period	8.5 (2.3)	7.3 (1.4)	8.1 (1.9)	8.7 (2.5)
Overall Mean	7.7 (1.9)		8.6 (1.9)	
Total Number of Words Correctly Recalled				
First Measurement Period	5.6 (3.5)	7.2 (1.1)	7.5 (2.3)	7.5 (1.4)
Second Measurement Period	7.5 (1.9)	6.4 (1.9)	7.6 (2.1)	8.0 (2.8)
Overall Mean	6.7 (2.1)		7.7 (2.2)	

Immediate Recall Task

	Control Immersion		Experimental Immersion	
	a.m.	p.m.	a.m.	p.m.
Reaction Time (ms)				
First Measurement Period	960 (164)	946 (161)	853 (221)	876 (171)
Second Measurement Period	971 (154)	925 (81)	836 (137)	828 (143)
Overall Mean	951 (140)		848 (168)	
Accuracy (percent correct)				
First Measurement Period	72 (10)	65 (20)	72 (7)	68 (11)
Second Measurement Period	67 (14)	63 (21)	64 (16)	64 (12)
Overall Mean	67 (16)		67 (12)	

Recognition Memory Task

	Control Immersion		Experimental Immersion	
	a.m.	p.m.	a.m.	p.m.
Signal Detection Rate (signals detected/min)				
First Measurement Period	9.6 (1.4)	9.7 (1.4)	9.6 (1.4)	9.7 (1.4)
Second Measurement Period	9.3 (1.8)	9.8 (1.8)	9.7 (1.5)	9.6 (1.2)
Overall Mean	9.6 (1.6)		9.7 (1.3)	
False Detection Rate (false detections/min)				
First Measurement Period	0.4 (0.6)	0.3 (0.3)	0.3 (0.3)	0.3 (0.4)
Second Measurement Period	0.2 (0.3)	0.2 (0.2)	0.3 (0.4)	0.2 (0.2)
Overall Mean	0.3 (0.4)		0.3 (0.3)	
Reaction Time to Signals (ms)				
First Measurement Period	585 (60)	559 (39)	538 (45)	518 (58)
Second Measurement Period	575 (41)	544 (40)	556 (42)	518 (45)
Overall Mean	566 (45)		533 (48)	

Dual Task: Visual Vigilance

	Control Immersion		Experimental Immersion	
	a.m.	p.m.	a.m.	p.m.
RMS Error				
First Measurement Period	2810 (727)	2803 (713)	2858 (559)	2689 (831)
Second Measurement Period	2577 (902)	2490 (551)	2628 (746)	2511 (814)
Overall Mean	340 (35)		350 (33)	
Number of Edge Violations				
First Measurement Period	33 (42)	26 (45)	30 (37)	22 (44)
Second Measurement Period	22 (31)	15 (42)	22 (31)	17 (45)
Overall Mean	340 (35)		350 (33)	

Dual Task: Compensatory Tracking

	Control Immersion		Experimental Immersion	
	a.m.	p.m.	a.m.	p.m.
Reaction Time (ms)				
First Measurement Period	2970 (668)	3219 (975)	2556 (386)	3105 (716)
Second Measurement Period	3026 (595)	2938 (810)	2567 (463)	2893 (506)
Overall Mean	3038 (762)		2780 (518)	
Number of Trials Completed				
First Measurement Period	60 (12)	55 (12)	69 (9)	58 (11)
Second Measurement Period	61 (12)	60 (15)	71 (7)	62 (11)
Overall Mean	59 (13)		65 (10)	
Accuracy (percent correct)				
First Measurement Period	86 (20)	83 (14)	81 (21)	87 (16)
Second Measurement Period	86 (17)	85 (17)	77 (27)	87 (13)
Overall Mean	85 (17)		83 (19)	

Verbal Reasoning Task

APPENDIX III

The Perceived Effects of Thermal Stress on Performance: Survey Questionnaire

DERA Centre for Human Sciences
Thermal Stress Questionnaire

The Centre for Human Sciences at DERA Farnborough has been tasked by MoD with investigating the effects of heat stress on military performance. As a key part of this programme, we are asking personnel who are exposed to hot climates during overseas detachments to identify the practical issues involved in living and working in high temperatures.

We are aware that you probably receive many requests to complete questionnaires. Our main reason for conducting this survey is to identify the most significant effects of working in extreme temperatures - this information will ensure that the heat stress research we do in the next two years is relevant to the needs of military personnel. In addition, if effective solutions to particular problems can be identified, we will try to ensure that these are applied.

We would be grateful if you could fill in this short questionnaire. All the information you provide will be treated in confidence. We ask you to give your name only because we may wish to contact you to discuss any points you raise, but if you prefer, you may complete the form anonymously

If you have any questions about filling in this form or if there are any issues that you would like to discuss further, you are welcome to contact us at the address at the end of the questionnaire.

Name and Rank ____________________________

Branch or Trade ____________________________

Today's date ________________ How long have you been on this detachment? ________ (weeks)

Q. 1 In general, do you like hot weather? (Tick one)

Yes ☐
No ☐
Neither like nor dislike it ☐

Q. 2 Do you like the climate on this detachment? (Tick one)

Yes ☐
No ☐
Neither like nor dislike it ☐

Comments

Q. 3 Is the temperature in your sleeping accommodation comfortable? (Tick one)

Yes	☐
No, too warm	☐
No, too cool	☐

Q. 4 Please indicate the approximate amount of time during a typical working day on this detachment that you spend:

Out of doors, without shade	☐	Mins/Hours (delete as appropriate)
Out of doors, in the shade	☐	Mins/Hours
Indoors, without air conditioning	☐	Mins/Hours
Indoors, with air conditioning	☐	Mins/Hours
Flying	☐	Mins/Hours

If you are aircrew, please answer Questions 5 & 6; if you are groundcrew, please go to Question 7

N.B. All questions about flying refer to daytime sorties during this detachment

Q. 5(i) Please describe your general thermal comfort while flying. (Tick one)

Uncomfortably cold ☐

Comfortable ☐

Uncomfortably hot ☐

(ii) Are there any particular phases of sorties (including ground phases) when you feel more uncomfortable? (Tick one)

Yes ☐

No ☐

If yes, please give details.

If you have reported no discomfort during sorties, please go straight to Question 6

(iii) What are the most significant causes of your thermal discomfort during sorties?

(iv) Does the duration of sorties affect your thermal comfort?

Yes, discomfort greater during longer sorties	☐
Yes, discomfort greater during shorter sorties	☐
No, comfort not affected by sortie duration	☐

Comments

(v) Are there any features of your flying clothing or equipment that could be changed to improve your thermal comfort?

(vi) Are there any other strategies to improve thermal comfort during sorties that you would like to see introduced?

Q. 6 How tired do you feel after a detachment sortie compared with a sortie of comparable duration and workload flown in the UK/Northern Europe? (Tick one)

More tired after a detachment sortie	☐
More tired after a UK/N.Europe sortie	☐
No difference in fatigue between the two	☐

Q. 7 Below is a list of several mental and physical activities. Please tick the boxes to indicate if the heat on this detachment is influencing your ability to carry out these activities; is your performance better, worse or unchanged in the heat? (Please tick one box for each activity)

	Don't Know/ Not Applicable	Better in Heat	Unchanged in Heat	Worse in Heat
Sustained concentration	☐	☐	☐	☐
Speed of reactions	☐	☐	☐	☐
Keeping information in memory for short periods (e.g. remembering a number you have just been told)	☐	☐	☐	☐
Mental alertness	☐	☐	☐	☐
Ability to do mental calculations	☐	☐	☐	☐
Ability to resist distraction	☐	☐	☐	☐
Ability to do delicate manual tasks	☐	☐	☐	☐
Ability to do physically strenuous work	☐	☐	☐	☐

Comments

Q. 8 Have you noticed any change in your mood in the heat? (Tick one)

Yes ☐

No ☐

If yes, please give details.

Q. 9 Are there any steps that could be taken to improve your thermal comfort on this detachment?

Additional comments

Thank you for completing this questionnaire. **Please return your questionnaire to Sqn Ldr R S Pearson.** If you have any questions or comments, please contact Elinor O'Connor, Centre for Human Sciences, DERA Farnborough, Hampshire GU14 0LX (Tel: Farnborough Ext. 4144)

APPENDIX IV

Experiment 3: Mean Values of the Performance Variables

	Control Exposure	Experimental Exposure
First Performance Assessment	290 (72)	281 (65)
Second Performance Assessment	273 (92)	286 (82)
Third Performance Assessment	281 (90)	281 (81)
Fourth Performance Assessment	272 (76)	270 (74)
Overall Mean	279 (83)	280 (76)

Fixed Foreperiod Simple Reaction Task: Mean reaction time (ms)

	Control Exposure	Experimental Exposure
First Performance Assessment	322 (61)	320 (59)
Second Performance Assessment	333 (80)	319 (52)
Third Performance Assessment	327 (115)	315 (63)
Fourth Performance Assessment	327 (52)	318 (69)
Overall Mean	327 (77)	318 (61)

Variable Foreperiod Simple Reaction Task (first presentation): Mean reaction time (ms)

	Control Exposure	Experimental Exposure
First Performance Assessment	356 (97)	346 (54)
Second Performance Assessment	368 (77)	356 (97)
Third Performance Assessment	353 (88)	347 (104)
Fourth Performance Assessment	356 (99)	334 (88)
Overall Mean	358 (90)	346 (86)

Variable Foreperiod Simple Reaction Task (second presentation): Mean reaction time (ms)

	Control Exposure	Experimental Exposure
Total Number of Words Recalled		
First Performance Assessment	7.3 (2.1)	7.8 (1.6)
Second Performance Assessment	7.5 (1.8)	8.2 (2.6)
Third Performance Assessment	8.2 (2.6)	7.3 (2.0)
Fourth Performance Assessment	7.7 (1.8)	8.0 (2.0)
Overall Mean	7.7 (2.1)	7.8 (2.1)
Total Number of Words Correctly Recalled		
First Performance Assessment	6.3 (2.0)	7.2 (1.3)
Second Performance Assessment	6.7 (1.9)	7.4 (2.2)
Third Performance Assessment	7.4 (2.5)	7.1 (1.7)
Fourth Performance Assessment	7.0 (2.0)	7.4 (1.9)
Overall Mean	6.9 (2.1)	7.3 (1.8)

Immediate Recall Task

	Control Exposure	Experimental Exposure
Reaction Time (ms)		
First Performance Assessment	931 (188)	954 (134)
Second Performance Assessment	935 (125)	912 (166)
Third Performance Assessment	945 (168)	890 (147)
Fourth Performance Assessment	877 (201)	899 (179)
Overall Mean	922 (171)	914 (157)
Accuracy (percent correct)		
First Performance Assessment	66 (9)	66 (14)
Second Performance Assessment	66 (13)	65 (16)
Third Performance Assessment	69 (15)	65 (12)
Fourth Performance Assessment	70 (11)	67 (11)
Overall Mean	68 (12)	66 (13)

Recognition Memory Task

	Control Exposure	Experimental Exposure
Signal Detection Rate (signals detected/min)		
First Performance Assessment	4.1 (1.6)	5.0 (1.4)
Second Performance Assessment	4.5 (1.6)	5.0 (1.6)
Third Performance Assessment	4.2 (1.7)	4.9 (1.8)
Fourth Performance Assessment	4.4 (1.6)	4.7 (1.7)
Overall Mean	4.3 (1.6)	4.9 (1.6)
False Detection Rate (false detections/min)		
First Performance Assessment	4.5 (2.1)	4.3 (1.8)
Second Performance Assessment	4.2 (2.4)	3.7 (2.2)
Third Performance Assessment	4.2 (2.5)	4.1 (2.0)
Fourth Performance Assessment	4.8 (2.3)	4.0 (2.3)
Overall Mean	4.4 (2.3)	4.0 (2.1)

continued

Vigilance Task

	Control Exposure	Experimental Exposure
Reaction Time to Signals (ms)		
First Performance Assessment	542 (63)	531 (68)
Second Performance Assessment	578 (96)	546 (83)
Third Performance Assessment	542 (60)	537 (81)
Fourth Performance Assessment	545 (76)	499 (82)
Overall Mean	552 (74)	528 (79)

Vigilance Task (continued)

	Control Exposure	Experimental Exposure
Reaction Time (ms)		
First Performance Assessment	3648 (729)	3580 (1381)
Second Performance Assessment	3826 (980)	3522 (1156)
Third Performance Assessment	3769 (860)	3334 (920)
Fourth Performance Assessment	3567 (646)	2913 (646)
Overall Mean	3703 (804)	3337 (1026)
Number of Trials Completed		
First Performance Assessment	48 (8)	51 (12)
Second Performance Assessment	46 (10)	52 (11)
Third Performance Assessment	47 (8)	54 (11)
Fourth Performance Assessment	49 (8)	62 (14)
Overall Mean	48 (9)	55 (12)

continued

Verbal Reasoning

	Control Exposure	Experimental Exposure
Accuracy (percent correct)		
First Performance Assessment	91 (11)	92 (10)
Second Performance Assessment	92 (10)	91 (8)
Third Performance Assessment	90 (9)	91 (11)
Fourth Performance Assessment	89 (12)	90 (11)
Overall Mean	91 (11)	91 (10)

Verbal Reasoning (continued)

	Control Exposure	Experimental Exposure
Reaction Time (ms)		
First Performance Assessment	437 (41)	426 (46)
Second Performance Assessment	436 (35)	418 (43)
Third Performance Assessment	436 (53)	423 (56)
Fourth Performance Assessment	427 (30)	405 (47)
Overall Mean	434 (40)	418 (48)
Accuracy (percent correct)		
First Performance Assessment	96 (2)	96 (2)
Second Performance Assessment	96 (3)	95 (2)
Third Performance Assessment	96 (2)	95 (2)
Fourth Performance Assessment	96 (2)	95 (2)
Overall Mean	96 (2)	95 (2)

Focused Attention Task: Overall reaction time and accuracy

	Control Exposure	Experimental Exposure
First Performance Assessment	456 (42)	448 (49)
Second Performance Assessment	453 (36)	440 (46)
Third Performance Assessment	451 (53)	439 (55)
Fourth Performance Assessment	443 (34)	421 (50)
Overall Mean	451 (41)	437 (50)

Focused Attention Task: Mean reaction time (ms) to trials in which the target letter differed to that in the previous trial

	Control Exposure	Experimental Exposure
First Performance Assessment	425 (44)	410 (46)
Second Performance Assessment	423 (44)	407 (44)
Third Performance Assessment	431 (54)	416 (57)
Fourth Performance Assessment	418 (32)	396 (46)
Overall Mean	424 (44)	407 (48)

Focused Attention Task: Mean reaction time (ms) to trials in which the target letter was repeated from the previous trial

	Control Exposure	Experimental Exposure
First Performance Assessment	31 (17)	38 (23)
Second Performance Assessment	30 (24)	33 (32)
Third Performance Assessment	20 (34)	23 (21)
Fourth Performance Assessment	25 (11)	25 (14)
Overall Mean	27 (22)	30 (23)

Focused Attention Task: Difference between mean reaction time (ms) to trials in which the target differed to that in the previous trial and trials in which the target letter was repeated from the previous trial

	Control Exposure	Experimental Exposure
First Performance Assessment	3 (51)	27 (21)
Second Performance Assessment	6 (34)	28 (48)
Third Performance Assessment	22 (46)	23 (32)
Fourth Performance Assessment	25 (26)	12 (36)
Overall Mean	14 (39)	23 (34)

Focused Attention Task: The Eriksen effect (ms)

	Control Exposure	Experimental Exposure
Reaction Time (ms)		
First Performance Assessment	545 (52)	516 (60)
Second Performance Assessment	540 (46)	510 (55)
Third Performance Assessment	545 (59)	508 (68)
Fourth Performance Assessment	526 (45)	502 (62)
Overall Mean	539 (51)	509 (61)
Accuracy (percent correct)		
First Performance Assessment	97 (2)	98 (3)
Second Performance Assessment	98 (3)	97 (4)
Third Performance Assessment	97 (3)	97 (3)
Fourth Performance Assessment	97 (4)	97 (4)
Overall Mean	97 (3)	97 (3)

Categoric Search Task: Overall reaction time and accuracy

	Control Exposure	Experimental Exposure
First Performance Assessment	557 (47)	530 (58)
Second Performance Assessment	556 (52)	530 (63)
Third Performance Assessment	560 (52)	529 (65)
Fourth Performance Assessment	541 (49)	514 (67)
Overall Mean	554 (50)	526 (63)

Categoric Search Task: Mean reaction time (ms) to trials in which the target letter differed to that in the previous trial

	Control Exposure	Experimental Exposure
First Performance Assessment	532 (53)	509 (60)
Second Performance Assessment	525 (42)	504 (50)
Third Performance Assessment	535 (65)	503 (67)
Fourth Performance Assessment	516 (41)	502 (57)
Overall Mean	527 (50)	505 (59)

Categoric Search Task: Mean reaction time (ms) to trials in which the target letter was repeated from the previous trial

	Control Exposure	Experimental Exposure
First Performance Assessment	25 (24)	21 (20)
Second Performance Assessment	31 (23)	26 (28)
Third Performance Assessment	25 (22)	26 (36)
Fourth Performance Assessment	25 (20)	12 (17)
Overall Mean	27 (22)	21 (25)

Categoric Search Task: Difference between mean reaction times (ms) to trials in which the target letter differed to that in the previous trial and trials in which the target letter was repeated from the previous trial

	Control Exposure	Experimental Exposure
First Performance Assessment	14 (17)	26 (16)
Second Performance Assessment	26 (19)	16 (20)
Third Performance Assessment	18 (21)	22 (27)
Fourth Performance Assessment	18 (18)	30 (18)
Overall Mean	19 (19)	24 (20)

Categoric Search Task: Difference between mean reaction times (ms) to trials in which the laterality of the target was compatible or incompatible with the laterality of the required response

	Control Exposure	Experimental Exposure
First Performance Assessment	16 (22)	12 (29)
Second Performance Assessment	20 (25)	22 (22)
Third Performance Assessment	25 (24)	18 (22)
Fourth Performance Assessment	16 (28)	25 (27)
Overall Mean	19 (25)	19 (25)

Categoric Search Task: The place repetition effect. Difference between mean reaction times (ms) to trials in which the target appeared in a different location to or the same location as that in the previous trial

	Control Exposure	Experimental Exposure
First Performance Assessment	23 (42)	36 (27)
Second Performance Assessment	24 (49)	26 (49)
Third Performance Assessment	23 (32)	32 (19)
Fourth Performance Assessment	30 (27)	38 (35)
Overall Mean	25 (38)	33 (33)

Selective Attention Tasks: SPUL ('spatial uncertainty little'). Difference between mean reaction times (ms) to trials in the Categoric Search task in which the warning crosses were presented close together, the laterality of the target and the required response were compatible, and no distractor was presented, and to trials in the Focused Attention task in which the warning crosses were presented close to the target location, and no distractors were presented

APPENDIX V

Experiment 3: Mean Values of the Performance Variables for the Participants who withdrew from the Experimental Condition

	Control Exposure	Experimental Exposure
First Performance Assessment	325	344
Second Performance Assessment	299	369
Third Performance Assessment	369	-
Fourth Performance Assessment	338	-

Fixed Foreperiod Simple Reaction Task: Mean reaction time (ms)

	Control Exposure	Experimental Exposure
First Performance Assessment	388	366
Second Performance Assessment	357	386
Third Performance Assessment	378	-
Fourth Performance Assessment	428	-

Variable Foreperiod Simple Reaction Task (first presentation): Mean reaction time (ms)

	Control Exposure	Experimental Exposure
First Performance Assessment	368	396
Second Performance Assessment	447	497
Third Performance Assessment	447	-
Fourth Performance Assessment	376	-

Variable Foreperiod Simple Reaction Task (second presentation): Mean reaction time (ms)

	Control Exposure	Experimental Exposure
Total Number of Words Recalled		
First Performance Assessment	8.0	5.5
Second Performance Assessment	8.0	6.5
Third Performance Assessment	8.5	-
Fourth Performance Assessment	6.0	-
Total Number of Words Correctly Recalled		
First Performance Assessment	7.5	5.0
Second Performance Assessment	8.0	6.0
Third Performance Assessment	8.0	-
Fourth Performance Assessment	6.0	-

Immediate Recall Task

	Control Exposure	Experimental Exposure
Reaction Time (ms)		
First Performance Assessment	1062	899
Second Performance Assessment	884	848
Third Performance Assessment	1029	-
Fourth Performance Assessment	889	-
Accuracy (percent correct)		
First Performance Assessment	69	56
Second Performance Assessment	68	65
Third Performance Assessment	70	-
Fourth Performance Assessment	66	-

Recognition Memory Task

	Control Exposure	Experimental Exposure
Signal Detection Rate (signals detected/min)		
First Performance Assessment	4.4	3.8
Second Performance Assessment	2.9	2.0
Third Performance Assessment	3.9	-
Fourth Performance Assessment	2.7	-
False Detection Rate (false detections/min)		
First Performance Assessment	3.6	3.8
Second Performance Assessment	2.4	2.0
Third Performance Assessment	3.6	-
Fourth Performance Assessment	1.8	-
Reaction Time to Signals (ms)		
First Performance Assessment	640	527
Second Performance Assessment	623	493
Third Performance Assessment	597	-
Fourth Performance Assessment	568	-

Vigilance Task

	Control Exposure	Experimental Exposure
Reaction Time (ms)		
First Performance Assessment	4102	3294
Second Performance Assessment	3777	3222
Third Performance Assessment	3951	-
Fourth Performance Assessment	3829	-
Number of Trials Completed		
First Performance Assessment	42	54
Second Performance Assessment	47	57
Third Performance Assessment	43	-
Fourth Performance Assessment	49	-
Accuracy (percent correct)		
First Performance Assessment	79	81
Second Performance Assessment	70	75
Third Performance Assessment	69	-
Fourth Performance Assessment	79	-

Verbal Reasoning Task

	Control Exposure	Experimental Exposure
Reaction Time (ms)		
First Performance Assessment	477	478
Second Performance Assessment	483	477
Third Performance Assessment	451	-
Fourth Performance Assessment	474	-
Accuracy (percent correct)		
First Performance Assessment	99	99
Second Performance Assessment	98	98
Third Performance Assessment	99	-
Fourth Performance Assessment	99	-

Focused Attention Task: Overall reaction time and accuracy

	Control Exposure	Experimental Exposure
Reaction Time (ms)		
First Performance Assessment	618	589
Second Performance Assessment	608	587
Third Performance Assessment	627	-
Fourth Performance Assessment	584	-
Accuracy (percent correct)		
First Performance Assessment	100	99
Second Performance Assessment	99	99
Third Performance Assessment	99	-
Fourth Performance Assessment	99	-

Categoric Search Task: Overall reaction time and accuracy

APPENDIX VI

Experiment 3: Coefficients of Correlation between Mood and Performance, and between the Physiological Variables and Performance

		Energetic Arousal			
		Performance Assessment			
		1	2	3	4
Variable Foreperiod RT (2nd presentation)	Control Hot	0.01 0.29	-0.06 0.19	0.23 -0.04	-0.06 -0.06
Verbal Reasoning: Overall RT	Control Hot	0.29 0.10	0.23 -0.02	0.20 -0.24	0.18 0.13
Verbal Reasoning: No. trials completed	Control Hot	-0.08 -0.21	-0.12 -0.07	-0.30 0.11	-0.29 -0.08
Vigilance: RT to signals	Control Hot	0.25 0.30	0.39 0.37	0.69 ** 0.05	0.48 0.23
Vigilance: Signal detections	Control Hot	0.39 0 00	0.05 0.24	0.05 0.01	-0.29 -0.17
Vigilance: False detections	Control Hot	-0.44 -0.48	-0.50 -0.27	-0.60 * -0.08	-0.30 -0.36
Recognition Memory: Accuracy	Control Hot	0.11 -0.34	0.21 0.17	0.20 -0.37	-0.21 0.14
Focused Attention: Overall RT	Control Hot	0.03 0.46	0.00 -0.08	-0.01 0.00	0.24 0.12
Focused Attention: RT to 'alternation' trials	Control Hot	-0.60 * -0.31	0.25 -0.08	0.53 * 0.03	0.46 -0.38
Focused Attention: RT to 'repetition' trials	Control Hot	-0.72 ** 0.03	0.08 0.06	0.36 0.04	0.43 0.27
Categoric Search: Overall RT	Control Hot	0.14 0.09	0.02 0.23	0.34 0.06	-0.15 **0.51** *
Categoric Search: RT to 'alternation' trials	Control Hot	-0.23 0.07	-0.01 0.12	0.39 0.16	0.20 0.47
Categoric Search: RT to 'repetition' trials	Control Hot	0.29 0.08	0.08 0.34	0.24 -0.03	-0.24 0.45

* $p < 0.05$
** $p < 0.01$
*** $p < 0.001$

		Tense Arousal			
		Performance Assessment			
		1	2	3	4
Variable Foreperiod RT (2nd presentation)	Control	-0.32	-0.22	-0.19	0.32
	Hot	0.02	-0.31	0.14	0.01
Verbal Reasoning: Overall RT	Control	-0.13	-0.17	-0.39	-0.11
	Hot	-0.36	-0.11	-0.10	-0.01
Verbal Reasoning: No. trials completed	Control	-0.13	-0.17	-0.39	-0.11
	Hot	-0.36	-0.11	-0.10	-0.01
Vigilance: RT to signals	Control	0.52	0.46	0.05	0.49
	Hot	0.41	-0.02	0.47	-0.02
Vigilance: Signal detections	Control	0.08	-0.09	0.06	0.23
	Hot	-0.03	-0.14	-0.20	0.22
Vigilance: False detections	Control	0.06	-0.12	-0.13	0.02
	Hot	-0.26	-0.07	-0.50	**-0.64** **
Recognition Memory: Accuracy	Control	-0.43	-0.19	-0.09	-0.21
	Hot	0.07	0.27	**-0.53** *	-0.32
Focused Attention: Overall RT	Control	0.33	0.07	0.06	-0.06
	Hot	0.35	**0.50** *	0.06	**0.60** *
Focused Attention: RT to 'alternation' trials	Control	0.26	0.10	-0.25	0.19
	Hot	-0.38	0.04	0.24	0.14
Focused Attention: RT to 'repetition' trials	Control	0.29	-0.02	-0.07	0.29
	Hot	-0.06	-0.12	0.18	0.31
Categoric Search: Overall RT	Control	0.01	0.33	-0.32	0.17
	Hot	0.12	0.22	0.24	0.35
Categoric Search: RT to 'alternation' trials	Control	0.01	0.17	-0.06	0.31
	Hot	0.17	0.21	0.35	0.40
Categoric Search: RT to 'repetition' trials	Control	-0.12	0.45	-0.37	0.03
	Hot	0.03	0.19	0.13	0.21

* $p < 0.05$
** $p < 0.01$
*** $p < 0.001$

		Hedonic Tone			
		Performance Assessment			
		1	2	3	4
Variable Foreperiod RT (2nd presentation)	Control	0.40	0.42	-0.01	-0.23
	Hot	0.23	-0.01	-0.17	-0.25
Verbal Reasoning: Overall RT	Control	0.20	0.44	0.64 **	0.54 *
	Hot	0.31	**-0.52** *	-0.26	-0.03
Verbal Reasoning: No. trials completed	Control	-0.28	-0.29	-0.46	-0.60
	Hot	-0.48	0.46	0.15	0.04
Vigilance: RT to signals	Control	-0.47	-0.44	0.17	0.05
	Hot	-0.12	-0.14	**-0.70** **	0.16
Vigilance: Signal detections	Control	-0.04	-0.05	-0.11	-0.08
	Hot	0.29	**0.56** *	0.18	0.03
Vigilance: False detections	Control	-0.15	-0.08	-0.15	-0.39
	Hot	-0.07	0.43	**0.65** **	0.33
Recognition Memory: Accuracy	Control	0.18	0.13	0.04	0.04
	Hot	-0.32	0.06	0.15	0.26
Focused Attention: Overall RT	Control	0.10	-0.10	0.20	0.54 *
	Hot	0.16	-0.24	0.24	-0.33
Focused Attention: RT to 'alternation' trials	Control	-0.29	-0.27	0.29	0.01
	Hot	0.36	-0.17	-0.30	-0.50
Focused Attention: RT to 'repetition' trials	Control	-0.61 *	-0.18	0.09	-0.17
	Hot	0.18	-0.07	-0.23	-0.33
Categoric Search: Overall RT	Control	0.16	-0.19	0.54 *	0.30
	Hot	**0.50** *	-0.10	-0.41	-0.42
Categoric Search: RT to 'alternation' trials	Control	0.28	-0.20	0.41	-0.01
	Hot	0.44	0.02	-0.42	-0.43
Categoric Search: RT to 'repetition' trials	Control	0.17	-0.23	0.45	0.34
	Hot	0.40	-0.24	-0.37	-0.31

* $p < 0.05$
** $p < 0.01$
*** $p < 0.001$

		Anger/Frustration			
		Performance Assessment			
		1	2	3	4
Variable Foreperiod RT (2nd presentation)	Control Hot	-0.76 *** 0.26	-0.44 0.24	-0.49 0.37	0.15 0.21
Verbal Reasoning: Overall RT	Control Hot	-0.24 0.15	-0.40 **0.77** ***	-0.31 0.21	0.38 0.30
Verbal Reasoning: No. trials completed	Control Hot	-0.02 -0.12	0.18 **-0.77** ***	-0.08 0.22	-0.31 0.21
Vigilance: RT to signals	Control Hot	0.25 0.48	0.28 0.15	0.00 **0.70** **	0.52 * 0.10
Vigilance: Signal detections	Control Hot	-0.42 -0.20	-0.32 **-0.68** **	-0.39 -0.38	-0.15 -0.30
Vigilance: False detections	Control Hot	-0.02 -0.44	-0.48 **-0.80** ***	-0.54 * **-0.64** **	-0.32 -0.25
Recognition Memory: Accuracy	Control Hot	0.09 -0.35	0.06 -0.35	-0.16 -0.35	0.20 -0.31
Focused Attention: Overall RT	Control Hot	0.44 **0.81** ***	0.61 * -0.10	0.51 * -0.02	0.35 0.12
Focused Attention: RT to 'alternation' trials	Control Hot	0.29 0.24	0.28 0.37	-0.03 **0.63** *	0.18 0.45
Focused Attention: RT to 'repetition' trials	Control Hot	0.50 0.46	0.30 0.28	-0.32 0.48	0.14 -0.03
Categoric Search: Overall RT	Control Hot	0.62 * 0.48	0.72 ** 0.11	0.13 **0.66** **	0.68 ** 0.12
Categoric Search: RT to 'alternation' trials	Control Hot	0.10 0.52	0.50 * -0.08	0.25 **0.68** **	0.32 0.05
Categoric Search: RT to 'repetition' trials	Control Hot	0.65 ** 0.26	0.81 *** 0.34	0.04 **0.61** *	0.55 * 0.18

* $p < 0.05$
** $p < 0.01$
*** $p < 0.001$

		Rectal Temperature			
		Performance Assessment			
		1	2	3	4
Variable Foreperiod RT (2nd presentation)	Control	0.16	0.07	-0.02	0.08
	Hot	-0.19	**-0.52***	**-0.58***	-0.24
Verbal Reasoning: Overall RT	Control	0.00	0.04	-0.08	-0.12
	Hot	-0.41	-0.41	-0.16	0.30
Verbal Reasoning: No. trials completed	Control	0.10	0.00	-0.08	0.30
	Hot	**0.74*****	0.40	0.42	-0.33
Vigilance: RT to signals	Control	-0.34	-0.06	-0.25	-0.28
	Hot	**0.61***	0.09	0.14	0.03
Vigilance: Signal detections	Control	0.15	-0.08	0.05	0.15
	Hot	0.12	0.15	0.26	**0.57***
Vigilance: False detections	Control	-0.43	-0.33	-0.16	0.20
	Hot	-0.17	-0.25	-0.09	-0.31
Recognition Memory: Accuracy	Control	0.23	0.33	-0.16	-0.08
	Hot	-0.29	0.09	-0.42	-0.31
Focused Attention: Overall RT	Control	-0.28	-0.40	-0.01	-0.24
	Hot	0.00	-0.50	**-0.73****	-0.30
Focused Attention: RT to 'alternation' trials	Control	-0.28	-0.37	0.00	-0.14
	Hot	-0.12	-0.46	**-0.65****	-0.22
Focused Attention: RT to 'repetition' trials	Control	-0.33	-0.45	0.00	-0.22
	Hot	0.16	-0.44	**-0.77*****	-0.34
Categoric Search: Overall RT	Control	-0.15	-0.51*	-0.19	-0.09
	Hot	-0.27	-0.37	**-0.65****	-0.41
Categoric Search: RT to 'alternation' trials	Control	-0.27	-0.49	-0.04	0.09
	Hot	-0.23	-0.48	**-0.64****	**-0.53***
Categoric Search: RT to 'repetition' trials	Control	0.09	-0.46	-0.23	-0.16
	Hot	-0.23	-0.16	**-0.64***	-0.15

* $p < 0.05$
** $p < 0.01$
*** $p < 0.001$

		Ramanathan Mean Skin Temperature			
		Performance Assessment			
		1	2	3	4
Variable Foreperiod RT (2nd presentation)	Control	0.14	-0.09	-0.28	-0.22
	Hot	-0.20	-0.04	0.01	0.13
Verbal Reasoning: Overall RT	Control	0.55*	0.35	0.06	0.18
	Hot	0.13	-0.21	0.03	-0.25
Verbal Reasoning: No. trials completed	Control	-0.10	-0.05	0.22	0.12
	Hot	0.13	0.40	-0.19	0.30
Vigilance: RT to signals	Control	0.23	0.22	-0.45	-0.49
	Hot	**-0.64****	-0.18	**-0.67****	-0.50
Vigilance: Signal detections	Control	0.48	0.69*	0.02	0.38
	Hot	0.15	0.25	0.28	0.12
Vigilance: False detections	Control	0.11	0.54*	0.28	0.38
	Hot	**0.60***	**0.52***	0.39	0.37
Recognition Memory: Accuracy	Control	0.05	0.06	-0.36	-0.32
	Hot	0.27	0.28	0.30	0.24
Focused Attention: Overall RT	Control	0.24	0.22	0.19	0.09
	Hot	-0.04	-0.13	0.00	0.19
Focused Attention: RT to 'alternation' trials	Control	-0.04	0.15	0.07	0.03
	Hot	0.06	-0.02	-0.09	0.26
Focused Attention: RT to 'repetition' trials	Control	0.20	0.16	0.24	0.13
	Hot	-0.19	-0.25	0.10	-0.01
Categoric Search: Overall RT	Control	0.15	-0.32	-0.19	-0.30
	Hot	0.25	0.21	-0.05	-0.05
Categoric Search: RT to 'alternation' trials	Control	-0.01	0.10	0.04	0.20
	Hot	0.31	0.39	-0.08	-0.07
Categoric Search: RT to 'repetition' trials	Control	0.09	-0.59*	-0.26	-0.40
	Hot	0.10	-0.07	-0.05	-0.02

* $p < 0.05$
** $p < 0.01$
*** $p < 0.001$

		Cheek Temperature			
		Performance Assessment			
		1	2	3	4
Variable Foreperiod RT (2nd presentation)	Control Hot	-0.09 ***-0.75****	-0.14 *-0.60*	-0.33 ***-0.74****	-0.14 *-0.14*
Verbal Reasoning: Overall RT	Control Hot	0.00 -0.55	-0.23 -0.22	0.04 0.02	0.08 0.16
Verbal Reasoning: No. trials completed	Control Hot	0.27 0.41	0.33 0.38	0.10 -0.07	0.09 0.08
Vigilance: RT to signals	Control Hot	0.06 0.24	-0.01 0.55	-0.48 -0.56	-0.28 -0.63
Vigilance: Signal detections	Control Hot	0.17 0.48	0.15 0.18	0.24 **0.74***	0.47 0.38
Vigilance: False detections	Control Hot	-0.45 -0.11	-0.09 0.28	-0.08 0.40	0.25 -0.02
Recognition Memory: Accuracy	Control Hot	-0.16 **0.64***	-0.07 **0.86****	-0.40 0.08	-0.32 0.35
Focused Attention: Overall RT	Control Hot	0.08 -0.20	-0.06 -0.15	0.21 -0.31	0.19 0.11
Focused Attention: RT to 'alternation' trials	Control Hot	-0.03 -0.20	0.03 0.01	0.23 -0.29	0.19 0.03
Focused Attention: RT to 'repetition' trials	Control Hot	0.09 -0.25	-0.17 -0.57	0.14 -0.34	0.17 0.22
Categoric Search: Overall RT	Control Hot	-0.64** 0.46	-0.62* 0.30	-0.40 -0.63	-0.16 0.62
Categoric Search: RT to 'alternation' trials	Control Hot	-0.57* 0.44	-0.48 0.40	-0.26 -0.46	0.05 0.50
Categoric Search: RT to 'repetition' trials	Control Hot	-0.49 0.37	-0.50 0.13	-0.34 **-0.68***	-0.15 0.63

* $p < 0.05$
** $p < 0.01$
*** $p < 0.001$

		Heart Rate			
		Performance Assessment			
		1	2	3	4
Variable Foreperiod RT (2nd presentation)	Control	0.27	-0.01	0.18	0.29
	Hot	-0.16	**-0.53***	-0.27	0.17
Verbal Reasoning: Overall RT	Control	0.43	0.10	0.29	-0.11
	Hot	**-0.54***	-0.29	-0.22	-0.29
Verbal Reasoning: No. trials completed	Control	0.16	0.31	0.15	0.31
	Hot	**0.89*****	0.28	0.24	0.27
Vigilance: RT to signals	Control	0.48	0.28	0.07	-0.20
	Hot	0.40	**-0.66****	-0.49	-0.43
Vigilance: Signal detections	Control	0.63*	0.38	0.42	0.40
	Hot	0.21	0.30	0.31	0.31
Vigilance: False detections	Control	0.11	0.29	0.04	0.17
	Hot	-0.11	0.35	0.14	-0.12
Recognition Memory: Accuracy	Control	0.12	-0.27	0.01	-0.41
	Hot	-0.28	0.46	-0.32	-0.13
Focused Attention: Overall RT	Control	0.21	-0.16	0.26	0.22
	Hot	-0.33	**-0.61***	-0.47	-0.25
Focused Attention: RT to 'alternation' trials	Control	-0.09	-0.11	0.13	0.24
	Hot	-0.35	-0.48	-0.42	-0.08
Focused Attention: RT to 'repetition' trials	Control	0.19	-0.28	0.33	0.13
	Hot	-0.24	**-0.71****	**-0.50***	-0.44
Categoric Search: Overall RT	Control	-0.26	-0.18	-0.11	-0.14
	Hot	-0.48	-0.42	-0.42	-0.39
Categoric Search: RT to 'alternation' trials	Control	-0.40	-0.10	-0.02	0.41
	Hot	-0.43	-0.41	-0.40	-0.43
Categoric Search: RT to 'repetition' trials	Control	-0.10	-0.17	-0.15	-0.37
	Hot	-0.38	-0.35	-0.44	-0.24

* $p < 0.05$
** $p < 0.01$
*** $p < 0.001$

		Variable: Salivary Cortisol			
		Performance Assessment			
		1	2	3	4
Variable Foreperiod RT (2nd presentation)	Control	0.69**	0.85***	0.79***	0.44
	Hot	0.35	-0.28	-0.20	0.07
Verbal Reasoning: Overall RT	Control	0.14	0.10	0.18	-0.58*
	Hot	-0.02	-0.16	**-0.52***	**-0.54***
Verbal Reasoning: No. trials completed	Control	-0.31	-0.19	-0.02	0.39
	Hot	0.20	-0.04	**0.52***	0.42
Vigilance: RT to signals	Control	-0.51	-0.61*	0.39	-0.14
	Hot	0.40	-0.12	0.33	0.23
Vigilance: Signal detections	Control	-0.15	-0.32	0.55*	-0.33
	Hot	-0.45	-0.17	-0.01	0.01
Vigilance: False detections	Control	0.32	0.19	0.30	-0.14
	Hot	**-0.60***	-0.36	-0.33	**-0.62***
Recognition Memory: Accuracy	Control	0.26	0.05	0.52*	0.46
	Hot	-0.49	-0.25	**-0.67****	**-0.68****
Focused Attention: Overall RT	Control	0.28	-0.10	-0.03	-0.05
	Hot	0.38	-0.03	-0.19	0.23
Focused Attention: RT to 'alternation' trials	Control	-0.40	-0.27	-0.25	-0.01
	Hot	0.15	0.09	-0.04	0.03
Focused Attention: RT to 'repetition' trials	Control	-0.79***	-0.20	0.00	-0.42
	Hot	0.17	0.12	-0.27	-0.21
Categoric Search: Overall RT	Control	-0.30	-0.05	-0.53*	-0.08
	Hot	-0.08	-0.02	-0.09	-0.08
Categoric Search: RT to 'alternation' trials	Control	0.41	-0.25	-0.27	-0.23
	Hot	0.03	-0.07	0.00	-0.06
Categoric Search: RT to 'repetition' trials	Control	-0.13	0.10	-0.43	-0.05
	Hot	-0.19	0.05	-0.16	-0.08

* $p < 0.05$
** $p < 0.01$
*** $p < 0.001$